Postural alignment and recovery of mobility after acquired brain injury

by

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Abbreviations used in this thesis

ABI	Acquired brain injury
ASIS	Anterior superior iliac spine
BoS	Base of support
CASP	Critical Appraisal Skills Program
COM	Centre of mass
COVS	Clinical Outcome Variables Scale
FIM	Functional Independence Measure
HiMAT	High Level Mobility Assessment Tool
ICC	Intraclass correlation coefficient
MDC	Minimum Detectable Change
PAD	Postural Alignment and Dispersion
TBI	Traumatic brain injury

Abstract

Recovery of mobility after acquired brain injury (ABI) can be limited, with many people never regaining independence with key motor skills such as walking. Few investigations have explored mobility progress for people who are unable to walk unsupported. Postural alignment is not typically included in kinematic studies, and its association with recovery of mobility is not clear. The central aim of this thesis is to determine if improvement in postural alignment is associated with improvement in mobility for people with severe mobility impairment after ABI.

The four studies in this thesis focus on this gap in the literature. To understand the impact of ongoing, severe mobility impairment after ABI, the thesis starts with a longitudinal, qualitative study exploring the significance of mobility for people with severe mobility impairment after ABI (Chapter 2). Relevant literature is then reviewed in a systematic review investigating the relationship between postural alignment and mobility (Chapter 3). Postural alignment was analysed in adults with severe mobility impairment after ABI and in healthy adults. This included development of a kinematic measure for whole-body postural alignment, the Postural Alignment and Dispersion (PAD) score (Chapter 4). Finally, a longitudinal, observational study of people with ABI who were unable to walk at eight weeks post-injury examined changes in their mobility over six months, and the relationship between mobility skills and postural alignment over time (Chapter 5).

Key findings from the qualitative study (10 participants, 26 interviews) were that mobility impairment was devastating and that “small” improvements such as assisted walking or transfers without a lifting machine were critical for their wellbeing. Based on data from seven publications, the systematic review was unable to determine whether postural alignment is related to mobility after ABI. Three-dimensional kinematic data from 14 adults with ABI and 14 healthy participants were analysed to develop the new PAD score. The score quantified body segments’ displacement from upright alignment over the base of support, measured in the transverse plane. Postural alignment was measured in sitting and standing, with and without support from rails. Repeatability was demonstrated in all conditions in healthy adults using intraclass correlation coefficients (ICC, range 0.701 to 0.945), and in the three conditions with sufficient data (sitting conditions and standing holding rails) in adults with ABI (ICC range 0.614 to 0.912). Dispersion of body segments was greater in participants with ABI. The difference in mean PAD scores between samples was statistically significant in sitting conditions, with higher scores in participants with ABI, reflecting greater mean segment displacements from upright alignment.

Over the six-month longitudinal study, adults with ABI (n=14) made significant progress with mobility based on scores on the Clinical Outcome Variables Scale (p=<0.001). Mobility improvement was significantly associated with improved postural alignment in sitting and standing, measured with PAD scores (p=<0.001 - 0.039).

In conclusion, the findings of this thesis have shown that improvements in mobility can be crucial for those with severe mobility impairment after ABI, and that aspects of mobility other than independent walking are meaningful for them. Marked impairments of postural alignment were noted in adult participants with severe mobility impairment after ABI, and despite the extent of their limitations they made significant progress with mobility over six months. Results provide preliminary evidence to support clinical reports that improvement in upright postural alignment is associated with mobility progress after ABI. This gives a basis for further investigation of postural alignment in kinematic research and provides new evidence to promote attention to postural alignment in rehabilitation practice.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

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Chapter 1

Introduction

1.1 Evidence-based background

Acquired brain injury (ABI) affects the lives of millions of people every year (Dewan et al., 2018, GBD 2016 Stroke Collaborators, 2019). Causes of ABI include stroke, trauma, hypoxia, and infection (AIHW, 2007). ABI can affect any aspect of an individual's function, and often multiple issues result, such as loss of physical independence, cognitive impairments, social isolation, and difficulty with communication (Turner-Stokes et al., 2015, Hawthorne et al., 2009). Effects can be profound and cause long-term changes in function and quality of life (Polinder et al., 2015). The ripple effect can extend widely, with potentially life-changing effects for family members, and difficulty returning to employment impacting the workforce (Ennis et al., 2013, van Velzen et al., 2009). ABI affects all ages, and has relatively high incidence in teenagers and young adults compared to other age groups, meaning many survivors have decades of their lives affected (AIHW, 2007, Te Ao et al., 2015, Hawthorne et al., 2009). For example, in New Zealand, incidence of moderate-to- severe traumatic brain injury (TBI) has been found to be twice as high in the 15-34 age group, compared to the rest of the population (Feigin et al., 2013).

People with ongoing impairments resulting from ABI may spend years working on recovery and attempting to re- establish quality of life (Eilertsen et al., 2010, Chamberlain, 2006). There can be high financial costs to society from hospital care and long-term support services (Humphreys et al., 2013, Dikmen et al., 2003). Lifetime cost of care after severe traumatic brain injury (TBI) has been estimated in the United Kingdom at around £1.3 million per case (Turner-Stokes et al., 2019). Importantly, this study also calculated that rehabilitation could achieve lifetime cost savings for individual cases of around £700,000. Despite this, people with severe mobility impairment after ABI are not always provided with rehabilitation (Forti et al., 2018, Lynch et al., 2015). People with non-ambulatory status between one and three months post-ABI have been reported as having limited prognosis for achieving independent walking (Katz et al., 2004, Preston et al., 2011). Presence of severe impairments can be used to suggest that they are not priority candidates for rehabilitation (Ilett et al., 2010, Kennedy et al., 2012). Therefore, improving outcomes for those who appear to have a poor prognosis is a priority for rehabilitation research.

Mobility can be defined as the means by which an individual moves about within the environment (Graham et al., 2004). Recovery of mobility after ABI has been studied extensively, primarily recovery of independent walking (Craig et al., 2011, Bland et al., 2011, Wonsetler and Bowden, 2017, Preston et al., 2011). Improvements in walking (Killington et al., 2010a), negotiating stairs (Alzahrani et al., 2009) and higher level mobility including running (Williams and Willmott, 2012) have been positively associated with aspects of quality of life such as societal participation, confidence, relationships and physical activity levels. These studies reinforce that better mobility can enhance opportunities and quality of life, however, severe limitations of mobility persist for a substantial proportion of survivors of ABI (Tate et al., 2012, Wolfe et al., 2011, Hammond et al., 2019). There is a paucity of evidence for recovery of mobility skills for those with severe deficits after ABI, with relatively little to guide clinical practice (McGlinchey et al., 2020). While recovering walking is prioritised highly by survivors of ABI and researchers (Luker et al., 2015, Rudberg et al., 2020), little is known about what matters most to those who have not recovered walking. As there are often multiple physical deficits following ABI (Hellweg and Johannes, 2008), understanding what is most meaningful for those with severe mobility impairment is vital to assist clinicians with prioritising areas for attention.

Postural alignment can be defined as the alignment of body segments relative to vertical and to each other when upright (Fortin et al., 2011). Analysis of posture in sitting and standing has included measurement of individual body segment angles in the sagittal or frontal planes (Fortin et al., 2011). In healthy participants, standing measurements of upper body angle and the angle of a line between neck and ankle have shown near-vertical alignment (Amabile et al., 2016, Krawczky et al., 2014). When studying people after stroke, inclination of the trunk has been found to be greater than healthy controls (Verheyden et al., 2014). A tilted trunk in sitting after ABI has also been associated with inability to sit independently (Piscicelli et al., 2016). However, kinematic studies have typically included participants who can stand or walk unsupported, affording limited understanding of the nature of these issues for people with more marked impairments. Further, it is not clear what improvement occurs in impaired postural alignment after ABI, suggesting that longitudinal investigation is needed.

Some kinematic and kinetic variables during walking have been studied extensively regarding their relationships with outcome after ABI (Schmid et al., 2013, Van Criekinge et al., 2017). For healthy walking, common analyses include velocity, stride characteristics and motion of ankle, hip and knee (Roberts et al., 2017). While lower limb motion is commonly studied, upper body motion or alignment are included infrequently (Roberts et al., 2017). An upright head and trunk in walking is usual in healthy adults (Kavanagh et al., 2006, Krebs et al., 1992, Begon et al., 2015), and it appears that the ubiquitous nature of this feature may have decreased the attention given to upper body alignment in kinematic research (Roberts et al., 2017, Schmid et al., 2013). Gait symmetry has been evaluated in many studies, but these have more commonly used measures of the legs or arm swing than postural variables (Viteckova et al., 2018). Findings from clinical studies featuring the upper body include greater trunk flexion during walking in people with TBI (Williams et al., 2009b), Parkinson's Disease (Cole et al., 2017) and spinal cord lesions (Johnson et al., 2009). Increased lateral displacements of trunk or head during walking have been found in people with stroke, TBI and Parkinson's disease, and been associated with such issues as falling and reduced walking speed (Cole et al., 2017, De Bujanda et al., 2003, Williams et al., 2009b reported in Mills et al., 2017). Despite this, evidence-based guidelines for neurological rehabilitation give no indication that there is any priority to assess or improve postural alignment (Stroke Foundation, 2019).

While there is a basis for including the upper body in kinematic analysis, the complexity of human kinematics makes determining the priority variables to examine difficult (Wonsetler and Bowden, 2017). In kinematic research, some variables may be selected based on having established methods for their extraction, rather than their clinical priority (Boyer et al., 2017). Although publications often provide data on individual segments, deviation of one segment can be expected to be accompanied by change in position or angle of others in the chain of segments (Simonsen, 2014, Carmo et al., 2012, Tyson et al., 2013), which influences how stable the body is over the base of support. A foundation concept in this thesis is that interpreting position of individual segments requires an understanding of how the body aligns overall, but a method for measuring whole-body alignment of multiple segments has not been identified in the literature.

Although postural alignment has attracted relatively little attention in rehabilitation research, interest in trunk performance after ABI has grown in recent years (Sorrentino et al., 2018, Van Criekinge et al., 2019). Trunk control is now considered a key variable for evaluating deficits in people with stroke or cerebral palsy, and has been reported to be associated with mobility performance (Carozzo et al., 2020, Van Criekinge et al., 2020, Verheyden et al., 2006, Heyrman et al., 2013, Van de Walle et al., 2012). However, as measures used to evaluate trunk performance do not score posture (Sorrentino et al., 2018), these studies do not elucidate the relationship between posture and mobility.

Posture influences how humans judge each other (Gilman, 2014, Millington, 2015). Variations in posture have been associated with many things including pain tolerance (Bohns and Wiltermuth, 2012), affective state (Hackford et al., 2019), depression (Kim et al., 2018, Rosario et al., 2014), creative thinking (Andolfi et al., 2017), voice production (Cardoso et al., 2019), verbal memory (Cohen et al., 2016), shoulder range of motion (Malmstrom et al., 2015, Kanlayanaphotporn, 2014), and swallowing (Alghadir et al., 2017). These examples provide broad support for the concept that posture influences human health and function, however, this has not been clearly determined after ABI. If a significant association between whole-body postural alignment and mobility impairment were demonstrated, this could provide a foundation for updating how mobility and kinematics are analysed.

1.2 Personal background to this research

I have worked in clinical brain injury rehabilitation for 19 years. What physiotherapy can offer to optimise progress for people with complex impairments after ABI has truly inspired me. There is some excellent evidence to guide ABI rehabilitation, but as my knowledge of the evidence base has grown, so too has my frustration with the gaps in evidence. Some of the most conspicuous gaps are for those with severe physical disability. Early in my career, as I began working with people who were too impaired to walk, evidence provided little guidance. I studied what these people could and could not do, and continually asked myself "What else could be contributing? What else is different from people who function easily?" Analysing their biomechanics provided an abundance of information, and I came to see that postural impairments were common. In some cases, the postural issues were isolated to the trunk and head. However, in many cases, postural alignment changed such that the whole body deviated excessively from the base of support. Observation of these patterns has helped to shape my practice, which has a strong focus on analysing biomechanics. As well as recognising the benefit of analysing the whole body, I learned that distinct deficits could be observed by checking frontal and sagittal views. I also noted many examples where improvement in postural alignment was accompanied by improvement in mobility. Hence, for many years I have been working to the clinical hypothesis that it is important to identify and address issues with postural alignment, to optimize mobility recovery. As much of my work has been with people with severe deficits, many are non-ambulant for an extended period. Some are too impaired to maintain anti-gravity positions in sitting and standing, even with assistance. Those who have not been able to improve postural alignment in anti-gravity positions have often made the least progress with mobility. This has given the impression that addressing mal-alignment is a priority to optimise physical progress. Despite the impression of success in clinical practice from working to address issues of postural alignment, this has not been reflected in published evidence. The lack of evidence to reflect this clinical pattern made it a clear choice for me to focus on in my research.

1.3 Aims of the thesis

The central aim of this thesis is to determine if improvement in postural alignment is associated with improvement in mobility for people with severe mobility impairment after ABI. Towards this, the investigations in this thesis will address the following aims:

1) Understand the significance of mobility for survivors of ABI with severe mobility impairment

2) Develop a valid, repeatable method of measuring whole-body postural alignment, suitable for people with severe postural issues

3) Determine if whole-body postural alignment is different after ABI, and if it becomes closer to healthy alignment over time

4) Establish changes made in mobility over 6 months in people with severe mobility impairment after ABI

5) Determine what association exists between whole-body postural alignment and mobility over time following ABI

1.4 Thesis structure

Chapters 2-5 in this thesis have been published, submitted for publication, or prepared for publication. As these chapters have been prepared as individual manuscripts, there is some repetition of content. There are formatting differences in each chapter due to the requirements of the individual journals, with some modifications made to the original manuscripts to assist readability. There are also modifications made to allow linking of chapters. References for all chapters are listed together, after the Discussion chapter.

Terminology: the term “non-ambulatory” is often used as a category for mobility status in research, however, this is variably defined. Some studies consider participants non-ambulatory if they walk on their own but require someone next to them (Preston et al., 2011). The focus for this research is on people with more profound physical impairment. Therefore, the term “severe mobility impairment” is primarily used in this thesis, rather than non-ambulatory. As there is no standard definition, the operational definition for severe mobility impairment used in this thesis is that the person could not be assisted to walk at all or could walk less than 10 metres with at least two assistants.

Chapter 2

Improving physical mobility is critical for wellbeing in people with severe impairment after an acquired brain injury: a qualitative study

This manuscript has been submitted for publication to the Journal of Physiotherapy:

Mills SJ, Mackintosh S, McDonnell MN: Improving physical mobility is critical for wellbeing in people with severe impairment after an acquired brain injury: a qualitative study

Abstract

***Questions**:* 1) What is the experience, and personal significance, of physical mobility skills for people with severe mobility impairment after acquired brain injury (ABI)? 2) How do these evolve over time?

***Design**:* Longitudinal, qualitative study.

***Participants**:* Ten adults who were not able to walk eight weeks after their ABI were recruited from inpatient rehabilitation.

***Methods**:* Participants were interviewed up to three times, with three months between interviews. Semi-structured interviews were transcribed verbatim and coded independently by two researchers, then themes developed. To analyse responses over time, codes were reviewed longitudinally. A third researcher reviewed themes against transcripts.

***Results**:* Initial analysis derived six themes: I lost everything overnight; It feels frustrating; Walking is absolutely the most important; I need help; I'm making progress; I can start doing things that I used to be able to do. Participants described overwhelming losses, with loss of mobility affecting many aspects of life. Recovery of mobility was prioritised very highly, especially walking. All participants described progress with mobility other than independent walking that was critical for their wellbeing, including assisted standing, assisted walking and transfers without a lifter. Themes from longitudinal analyses included: My losses softened by progress; Walking means freedom; Control helps adjustment happen; Challenges keep coming. Over time, participants valued greater control within their lives and progress with mobility was a key factor.

***Conclusion**:* Participants saw mobility as crucial to recovering their options and control of life. Many mobility achievements other than independent walking were prized, including assisted mobility.

2.1 Introduction

Acquired brain injury (ABI) can result in profound loss of skills and changes in lifestyle, with these losses described as devastating, frustrating and isolating (Lou et al., 2017, Salter et al., 2008, Levack et al., 2010). ABI affects all ages, with causes including stroke, trauma, tumours and infection (Teasell et al., 2007). Recovery of mobility is often the highest priority for survivors of ABI, and is a common focus in rehabilitation (McGlinchey et al., 2020, Tornbom et al., 2017, Luker et al., 2015). Evidence indicates that rehabilitation is effective for progressing mobility after ABI (Turner-Stokes et al., 2015), and some studies demonstrate improvements for people with severe impairment (Jackson et al., 2000, Hammond et al., 2019, Smania et al., 2013). However, the likelihood of recovering mobility skills can decrease with time (Katz et al., 2004, Jorgensen et al., 1995). Less than 20% of people who are unable to walk independently at two months post-injury have been reported to progress to independent walking (Katz et al., 2004). Despite the evidence for ABI being a life-changing event and mobility being crucial for recovery (Lou et al., 2017, Salter et al., 2008), the personal significance of mobility skills for those who have not recovered independent walking is not clear. No study has focused on experiences and priorities of people with severe mobility impairments after ABI.

Adapting to changes resulting from ABI can be a lengthy, difficult process over many years (Fadyl et al., 2019, Levack et al., 2010). Little is known about how people adapt to severely impaired mobility, and how this evolves in the early months post-ABI. Mobility skills have been shown to be important for quality of life after ABI, but studies have focused on people who already walk independently (Killington et al., 2010a, Williams and Willmott, 2012). The aspects of mobility that are most valuable to people who have not recovered independent walking are not known. To understand recovery after ABI, all individuals' perspectives are important, regardless of the progress made (Whiffin et al., 2015). Greater understanding of the priorities for those who have severe impairments after ABI will inform rehabilitation practice.

The research questions were:

1) What is the experience, and personal significance, of physical mobility skills for people with severe mobility impairment after ABI?
2) How do their experiences and perceptions evolve over time?

2.2 Methods

2.2.1 Design

For this longitudinal, qualitative study, an Interpretive Descriptive approach was used, seeking to understand patterns and exceptional instances in participants' subjective perspectives that could inform clinical practice (Thorne et al., 2004). This method draws on the understanding that experiences of human health are influenced by complex interactions between psychosocial and biological factors, which are individual to each case (Thorne et al., 1997). A social constructionist perspective also influenced study design, recognising that the participant's experience is their reality, and analysis of participants' self-reported experiences can provide clinicians with alternative understandings than those developed in clinical practice (Charmaz, 1990). As the human experience of illness and disability changes, longitudinal analysis of three-monthly interviews explored their experiences over time (SmithBattle et al., 2018). The COREQ (COnsolidated criteria for REporting Qualitative research) Checklist was used to guide reporting (Tong et al., 2007).

2.2.2 Participants

Participants were drawn from a longitudinal study of mobility recovery after ABI, recruiting from consecutive admissions to inpatient ABI rehabilitation. Inclusion criteria required that they were not walking at eight weeks post-ABI (maximum score of two on items eight and nine of the Clinical Outcome Variables Scale)(Low Choy et al., 2002) and that they could understand simple questions and communicate sufficiently to enable interview participation, as advised by their Speech Pathologist. Participants could enter the study at any time during inpatient rehabilitation, after eight weeks post-ABI. Repeat interviews occurred at three-monthly intervals from the initial interview. Exclusion criteria were severe amnesia or confusion that precluded participation in interviews. Eligible participants and guardians were approached face-to-face to seek informed consent to participate.

2.2.3 Procedures

Semi-structured interviews were conducted at a rehabilitation facility, via video call, or at the participant's home. Interviewers used a written guide, developed by the researchers, which evolved over time (SmithBattle et al., 2018). Core questions were asked flexibly based on participants' abilities and responses (Table 2.1). Questions were initially broad, for the interview to evolve gradually, without premature findings (Thorne et al., 2004). When participants didn't interpret a question as intended, it was typically rephrased, and if not successful, it was left and possibly returned to later. Participants were given the opportunity to comment on their perspectives over time, but when limited by memory impairment, present thoughts were the focus. To verify the data as it emerged, responses were confirmed during interviews as much as was practical. Interviews were audio recorded and transcribed verbatim. Interviewers kept field notes during and/or after interviews, which were included in analysis. Participant checking of transcripts was not used, as it was expected that this may not be achievable for all participants. Participants could choose to have a support person present; when this occurred, they were advised that they were welcome to comment during the interview, but the focus would be on the participant. All support persons were family members; their comments were also transcribed and included in analysis. Researcher checking of transcripts against recordings was completed prior to analysis. For reporting, each participant was allocated a pseudonym.

2.2.4 Research team, rigour and reflexivity

All researchers were physiotherapists with over 15 years of experience including neurological rehabilitation and/or qualitative research. MNM and SM had doctoral degrees; SJM was undertaking a higher degree by research and worked at the study site at the time. Most interviews were conducted by an experienced qualitative interviewer external to the research team. Reflexivity was aided by the varying backgrounds of the researchers, also by the longitudinal design, as analysis had to be open to participants' perspectives changing over time (Carduff et al., 2015). Following analysis by two researchers, a third researcher added another layer of review, to assist with the credibility of findings.

Table 2.1 Semi-structured interviews: core questions

Tell me about your life before your brain injury/stroke.
Tell me about the last week, and how your days have looked.
Have you had any achievements in terms of being able to get up and get around in the last couple of months?
What stands out as the most important movement ability for you in the last couple of months?
I'd like to hear a bit more about the times lately when you've had help to get up and get around.
Have you gone out with friends/family?
Are there things that you're aiming for in the next few months?

2.2.5 Analyses

Line-by-line first and second cycle coding were completed independently by two researchers (SJM, MNM) using NVivo software (QSR International, v12). To answer the first research question, codes from all interviews were discussed and refined, before being grouped into themes. Transcripts were reviewed again by each researcher against the themes. A third researcher (SM) then reviewed and discussed transcripts and themes. Data saturation was not targeted as the nature of the enquiry was expected to produce highly diverse data.

For longitudinal analysis, a trajectory approach was used (Grossoehme and Lipstein, 2016). Data from each code, for the nine participants who had done multiple interviews, were organised longitudinally in a table. The data for each participant were reviewed independently by MNM and SJM. Longitudinal patterns were described for each code. The two researchers then revised these patterns into categories, using a manual mapping technique where individual items were moved around on a table as categories were explored (Fadyl et al., 2017). Categories were then refined into themes and discussed with SM.

2.3 Results

From 252 consecutive admissions to ABI rehabilitation, 32 were not walking at eight weeks post-ABI, and 14 participated in the study of mobility recovery. Eighteen did not participate in the study of mobility recovery, details are provided in Chapter 5. Ten of these (5 male, 5 female) consented to participate in the qualitative study. ABI was traumatic (n=5), stroke (n=4), or hypoxic (n=1). Exclusions were due to severe amnesia (n=3) and severe communication impairment (n=1). Average age at first interview (December 2015 – July 2017) was 43 years, range 20-75 years. Twenty-six interviews were completed; seven participants completed three interviews, two completed two, and one completed one. Eight participants entered the study later than 8 weeks post-ABI; mean time from injury to first interview was 123 days (range 56 -310 days). Interviews were 15 – 80 minutes long. All ten participants' interviews were included in the initial analysis, and the nine participants who did repeat interviews were included in the longitudinal analysis. Six participants chose to have a family member present during some or all of their interviews. Three interviews were conducted by MNM, five by SJM and 18 by the external researcher.

2.3.1 *Initial analysis* - personal significance of physical mobility was described in six themes, shown with their contributing codes (Table 2.2).

I lost everything overnight

Participants described devastating losses following ABI. Several of the interviews were highly emotional, with frequent crying. Much of the focus of their distress related to their loss of mobility, and the impact that this had on losing independence with basic aspects of life, their lack of opportunity to get away from hospital, and subsequent helplessness. Several participants likened this to being in prison. Each participant described that they had no mobility restriction prior to their ABI. Loss of dignity was distressing to many participants. For example, Anne, 45, expressed:

"That's denigrating having to wear nappies and being put in one of those joeys [lifters] and having to wait for permission to eat some of the foods."

The inability to get to the toilet on their own, experience of incontinence, and the loss of privacy with showering, were described as humiliating. Loss of privacy also related to being in a hospital setting where personal information was discussed among many people.

Table 2.2 Themes and their contributing codes

‘I lost everything overnight ‘	**‘It feels frustrating’**	**‘Walking is absolutely the most important’**	**‘I need help’**	**‘I’m making progress’**	**‘I can start doing the things that I used to be able to do’**
Control	Challenges of rehab	True meaning of mobility changes	Feelings about needing help with everyday activities	Facilitators to progress with mobility	Recovering lifestyle
Dignity	Frustrations	Barriers to mobilisation	Carer impact	Signs of progress	Aspirations
Loss of independence	Other barriers	Identity		Being given the chance to try	
Loss of lifestyle	Emotional health	Big achievements		Recovering independence	
	Risks			Rehab is hard	
	Being given the chance to try			Coping	
				Hope	
				Feeling normal	
				Big achievements	
				Feelings about progress with mobility tasks	

It feels frustrating

Participants described a wide array of frustrations. Many of these related to lack of choice and loss of control. There was regular frustration with the difficulty of day-to-day tasks, requiring more time or effort than previously, and relying on others to allow things to happen. Participants' loss of mobility was central to their frustrations, when they were dependent on others to move anywhere. When asked *"how does it feel to get help with things like getting in and out of bed?"* Cheryl, 51, responded:

"It feels frustrating as any feeling you can ever imagine… when your whole choice is taken away from you like that it's an absolute slap in the face to your dignity."

Participants spoke of the experience of transfers in a lifting machine as being particularly traumatic. They felt that staff seemed willing to assist transfers more often when they progressed to a standing transfer. Several participants also described traumatic experiences where they felt that staff were not considerate or respectful towards them. Even if these were sporadic, it appeared that these occasions were particularly difficult to cope with when staff were relied on frequently for assistance, and in the context of their overall losses and challenges. There was also frustration with the array of barriers that participants contended with, such as fatigue and pain. Slowness of progress was an ongoing frustration for some, while others indicated that they could accept their rate of improvement. Participants felt frustrated with the profound loss of usual life routines and interactions, and often felt desperate to have time away from the hospital but felt that this took too long to commence. Cheryl, 51, commented:

"I would like to go out, just out, just … to a shop, just feel a bit normal."

I need help

Participants spoke frequently about the experience of needing help, and of receiving help. Alongside the frustration of requiring help throughout the day and night, was the challenge of asking for it. Participants described this as difficult to adjust to, and several described negative experiences when staff seemed to discourage them from asking for help. Furthermore, there was a common frustration of how long it could take for help to arrive.

This was particularly problematic when multiple assistants were required. Anne, 45 commented:

“It takes, like half an hour to get the nurses, if you need to go to sleep or if you need to go to the toilet, and when you wake up, you end up wetting your pants.”

Having help from a family member was preferred over help from staff, although there were also reports of feeling like a burden on family. Other comments indicated that staff help was appreciated, such as from Sue, 42:

“Without that help I’m up shit creek.”

Several participants commented about needing permission to try tasks alone or away from therapy appointments and were not engaged in the decision-making process about tasks that they could try for themselves.

Walking is absolutely the most important

Walking was the outstanding priority for participants to recover. Walking seemed to represent independence, freedom, and a return to their previous lifestyle more than any other aspiration. Using a wheelchair was difficult to accept for many participants. While interviews also identified other progress that was prized, walking was maintained as the highest priority overall. When asked *“how do you rate walking compared to any other priorities for your recovery?”* Troy, 22, responded:

“Oh, that's at the top, none of the priorities there would come close.”

I’m making progress

The most frequent interview comments came from participants discussing their progress and achievements. All participants described progress that was valued and meaningful for them. Interestingly, there were many achievements that they prized other than independent walking, such as assisted standing, assisted walking, assisted car transfers, powered wheelchair mobility and progressing from lifter transfers. When asked “What's the important thing been, with your improvements with getting up and around?” Troy, 22, replied:

“Well pivoting I guess, like pivoting [pivot transfers] it's just opened up my world, up to a new life.”

While participants regarded these achievements highly, they also typically discussed them as stepping stones to further progress, rather than outcomes that they saw as an end-point. Powered wheelchair mobility was highly valued by some participants when it provided them with their only independence with mobility. Several participants also spoke of the difficulty in learning to use one. Some participants commented about using a manual wheelchair on their own, although this wasn’t raised as positively, with reports of feeling self-conscious in a manual wheelchair.

Most participants regained independent toileting, which was valued highly. Mobility skills that were prized also included managing stairs (with and without assistance), recovering their driver’s licence, ceasing use of a wheelchair, and specific progress with walking such as further, faster, with reduced help, or without an aid.

Participants described the boost to their optimism and hope that came from achieving mobility tasks with assistance. Hope also came from the encouragement they received from staff, from seeing others make progress and from recognising signs of their own progress. There were many comments about the positive impact that rehabilitation had on recovery. Physiotherapy was the factor mentioned most often as aiding participants’ progress, and many described that they wanted more physiotherapy.

I can start doing things that I used to be able to do

Participants described adapting to their situation and to their limitations, despite the extent of their losses and frustrations. There were fewer comments within this theme, and these were more prevalent at later interviews. Adaptation was most often linked with experiences that were more “normal”, such as spending time with family and friends, and being away from the hospital. Some participants described relatively small adjustments from their previous lifestyle. Scott, 29, commented about walking:

"For longer distances, I need the stick, or at least I bring it with me, in case I do need it."

Other comments described that considerable planning was required for simple activities, for example, from Tracy, 41:

"So whilst it's good to get out, it's just thinking about the right outing and my mother says 'I'll take you for a drive' well that's nice, because you can look at things, but you still need to stop and go to the bathroom, so it's another transfer in and out the car. So you really do need to plan your activities."

2.3.2 Longitudinal analysis – four themes were developed to describe how the personal significance of mobility evolved over time: My losses softened by progress, Walking means freedom, Control helps adjustment happen, Challenges keep coming.

My losses softened by progress

The impact of losses on participants remained high over time. While there were indications of participants becoming accustomed to their changed capacity, overall, they didn't appear to update self-concepts to accept disability. Participants kept striving to recover what they had lost throughout their time in the study, which was up to 10 months post-injury. The factor that seemed to help most with mitigating this impact was progress. Troy, 22, shared:

"I was really embarrassed when my injury first happened, but now I'm not so embarrassed, considering what I can do now."

Walking means freedom

Recovering the ability to walk remained the top priority for participants over the duration of the study. Those who achieved independence in a wheelchair continued to focus on recovering walking. Those who accomplished independent walking reported it as their most important achievement. For example, when asked *"what has been the most significant thing in your recovery?"* Caleb, 20, asserted:

"Obviously, walking."

Control helps adjustment happen

Adjustment to changes after ABI was apparent between interviews, and the nature of this varied between participants. Achieving elements of control appeared to assist participants to think beyond their focus on aspirations like walking, to lifestyle areas such as home and family roles, or work. When asked *"You said you've come to terms with your powered chair. Can you tell me more?"* Tracy, 41 responded:

"That you can have a life with the chair."

While greater control for most participants came with increased physical independence, it also came with learning to be in charge, such as instructing carers in their role to assist transfers.

Challenges keep coming

Some challenges that participants described were raised repeatedly over time, while others were raised at only one time-point. Being seen in a wheelchair was difficult for some to adjust to, and this was usually raised at the first interview. Frustrations with staying in hospital accumulated over time for some participants, such as distress related to interactions with staff, and frustration with the expectation of conforming to hospital routines. Cheryl, 51, commented:

"I actually think some of the nurses here sort of forget how it is."
Interviewer: *"What do you feel they forget?"*
"Just to be sensitive to the emotional state of people like me. I am an achiever usually."

2.4 Discussion

The devastation that participants described following ABI, and how strongly they centred their losses around their inability to move themselves from place to place, reinforces the importance of mobility skills for quality of life. While independence with walking was prized most highly, all participants described other aspects of mobility that were important. This improved understanding of the mobility skills that matter to people who have severe disability in the early months post-ABI is valuable for clinical practice, and for guiding future research.

Our findings indicate that some commonly used measures of mobility, such as the Functional Ambulation Classification, Motor Assessment Scale, Barthel Index, or Functional Independence Measure, may not reflect some of the progress that matters to people with severe impairment after ABI. The difficulty for measurement tools to capture meaningful changes is highlighted by the range of achievements that mattered to participants, such as assisted standing, assisted car transfers and progressing from lifter transfers. Accordingly, progress with mobility which is meaningful to an individual after ABI may not result in change on some measurement tools. The floor effect of some tools limits their ability to demonstrate change when a range of skills all score the lowest value (Stubbs et al., 2014). For example, the Functional Independence Measure would score a chair transfer performed with a mechanical lifter and two assistants at the same level as a chair transfer performed by walking a few steps with two assistants, whereas participants indicated these are worlds apart. It may be that some measures evaluate service providers' needs more than items that matter to the individual. Change in function that does not result in change to a score could be interpreted as not meaningful. This raises questions about how outcome can be best evaluated, so that meaningful change is not missed. Reviewing achievement of goals is a valuable component of evaluation for individuals and attaining goals is associated with benefits such as lower levels of depression (Brock et al., 2009). However, a measure of the extent to which a goal is achieved is also needed. Goal attainment scaling offers a method to address this, by measuring outcome on an individual's goal, scored in a standardised way (Turner-Stokes, 2009).

Despite the importance placed by participants on recovery of skills such as assisted standing and assisted walking, evidence is lacking for interventions to recover these skills after severe ABI (McGlinchey et al., 2020). Needing physical assistance is common, yet providing assistance in the presence of complex and severe impairments can be difficult (Karnath, 2007). Many people rely on family for physical assistance and needing to assist mobility can increase carer strain (Pont et al., 2020, Zhu and Jiang, 2018, Piccenna et al., 2017). Nursing injuries resulting from patient handling have been given substantial attention in clinical research, with strategies such as the “No Lift” policy evaluating increased use of transfer equipment to reduce injury levels (Engkvist, 2006). This has resulted in equipment such as mechanical lifters being used more commonly, while participants in the present study have indicated that this method is particularly disliked. Further research is needed to determine how methods for assisting mobility can achieve a balance of function, safety, dignity and facilitating progress.

Participants spoke of how trapped they felt in hospital, and how they felt that they waited too long for the chance to do things like take leave from the hospital with family. Participants indicated that they wanted the chance to try skills like standing or car transfers as early as possible, to explore their capabilities and to give more choices. This raises questions about how the priorities for assessments in rehabilitation are determined. The boost that participants described from experiences such as achieving standing with help or transfers without a lifting machine indicates the value of exploring options to achieve these, as early as possible. Therefore, approaches that are client-centred and prioritise the items to include may be beneficial. Also, focussing clinical assessment on the items within a standardised scale may not cover all priorities.

The findings must be considered in context of the study’s limitations. All participants were admitted to inpatient rehabilitation and all made progress with mobility skills, so the experience of people with ABI who were not accepted for rehabilitation and/or those who did not progress is missing. Cognitive and communication impairments were noted during some interviews, such as when carers corrected comments from participants, or comments were limited by word-finding or memory. More frequent longitudinal interviews could assist with gathering additional details (Carduff et al., 2015).

All researchers in this study were physiotherapists, providing a useful foundation to understand participants' comments, however, also a potential bias with interpretation of the data.

Our findings suggest that adults with severe mobility restriction after ABI focus strongly on the ability to walk again; however, they also value other achievements that provide hope, greater control and sense of "normal" in their lives. Finding ways to increase the amount of progress for people with severe physical impairment after ABI appears imperative.

Chapter 3

Is there a relationship between postural alignment and mobility for adults after acquired brain injury? A systematic review

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Following the manuscript, advances in evidence since this review was published are summarised.

Abstract

***Primary objective**:* to examine the relationship between postural alignment and mobility skills for adults after acquired brain injury (ABI).

***Methods**:* Systematic review of the literature. Relevant databases and grey literature were searched, and reference lists of shortlisted publications. Studies were included if participants were adults with ABI, they measured both postural alignment and mobility and analysis included a relationship between alignment and mobility. Those that met inclusion criteria were assessed with a critical appraisal tool. The review was registered with PROSPERO, registration number CRD42015019867.

***Results**:* Seven observational studies were included that had examined a relationship between postural alignment and mobility after ABI. Critical appraisal scores were moderate to strong. While some studies reported that improved postural alignment was related to improved mobility after ABI, results varied and there was insufficient evidence to answer the primary question. Heterogeneous study designs did not allow meta-regression.

***Conclusions**:* A small amount of observational evidence exists investigating postural alignment and its relationship to mobility after ABI. Results vary with some studies reporting that a more stable, upright trunk correlates with better mobility, and others providing conflicting or ambiguous results. Further research is needed to establish the relationship between postural alignment and mobility skills after ABI.

3.1 Introduction

Mobility impairment is a highly disabling effect of acquired brain injury (ABI) in adults (Williams and Willmott, 2012, van de Port et al., 2006). The aetiology of ABI is diverse, and can include stroke, traumatic brain injury (TBI) and other non-traumatic injuries such as hypoxia (AIHW, 2007). The initial event often results in a high cost to the health system, with long acute and sub-acute hospital lengths of stay (Arango-Lasprilla et al., 2010, Humphreys et al., 2013). However, physical limitations that result from ABI may continue for decades and relate to life-long restrictions in lifestyle (Dawson and Chipman, 1995, Tate et al., 2012). The impact of ABI is wide–reaching, with 2.2% of the adult population having ABI- related disability (AIHW, 2007). Survivors of ABI can have marked changes in independence, relationships, ability to achieve employment and ultimately in self-concept (Douglas, 2013, Ownsworth and Haslam, 2016, van Velzen et al., 2009, Wood et al., 2005). Burden on family carers of adults with ABI can be very high, including psychological stress and social isolation (Perry and Middleton, 2011, van Heugten et al., 2006). The magnitude of the impact of ABI emphasises the importance of research to enhance outcomes and quality of life for survivors.

Mobility has been described broadly as a person's independence in moving about the home or community (Perry et al., 1995), and specifically as discrete skills such as walking and climbing stairs (Iezzoni et al., 2001, Green et al., 2002). Walking is commonly rated as the highest priority for people surviving ABI (Bohannon et al., 1988, Craig et al., 2011) and improved mobility after ABI has been shown to correlate with improved quality of life (Williams and Willmott, 2012, Killington et al., 2010a). Multiple factors have been identified that relate to limited mobility after ABI, such as reduced muscle strength (Ada et al., 2006, Killington et al., 2010b, Teixeira-Salmela et al., 2001, Kim and Eng, 2003), reduced muscle power (Williams et al., 2010a, Williams et al., 2013a), reduced cardiovascular fitness (Hassett et al., 2011), balance impairment (Basford et al., 2003, Garland et al., 2007, Howe et al., 2006), cognitive impairment (Cantin et al., 2007, Jackson et al., 2000, Perry et al., 2006) and reduced balance confidence (Inness et al., 2011, Ng, 2011). In biomechanical studies, factors that have correlated with improved walking performance after ABI include less lateral pelvic displacement (Dodd and Morris, 2003, Williams and Schache, 2010, Tyson, 1999) and greater ankle power generation at push-off (Williams et al., 2013b, Williams et al., 2010b). Upper body alignment has been given very little attention in biomechanical studies of walking (Chung et al., 2010, Sartor et al., 1999), despite the large volume of research undertaken. During preparation of this publication a brief search of Scopus and Web of Science for biomechanical studies of walking after brain injury showed high yield with over 2000 titles, yet the present review found that almost all biomechanical studies focused exclusively on the legs. While it has been demonstrated that a stable, upright trunk is a key feature of healthy walking (Cromwell et al., 2001, Krebs et al., 1992, Sartor et al., 1999), the upper body is rarely examined in studies of mobility after ABI. A similar trend of a lack of data collection on the upper body, and lack of analysis of upper body data, has also been reported in other areas of research with neurological conditions, such as cerebral palsy (Romkes et al., 2007).

Several studies have compared the upper body during mobility after ABI with healthy adults. Trunk flexion was significantly greater during walking in people with TBI compared with healthy adults, with no significant difference in lateral flexion (Williams et al., 2009b). This study demonstrated many important features of walking after TBI, including a high prevalence of pelvic and trunk abnormalities, but didn’t examine a relationship between alignment data and mobility data. Verheyden et al. (2014) evaluated spinal alignment and found that the participants with stroke had significantly more forward inclination of the trunk than the healthy control group in standing. They reported that in the participants with stroke, more forward inclination of the trunk in standing correlated with lower scores on the Berg Balance Scale, indicating that the more upright participants performed better on that test. Trunk symmetry has also been evaluated in a group of survivors of stroke; those who showed trunk deviation towards their weaker side in sitting scored significantly lower on mobility using the Rivermead Mobility Assessment at 3 and 6 weeks following stroke (Taylor et al., 1994). Presence of unilateral neglect correlated significantly with trunk deviation towards the weaker side.

Several studies have also compared performance of trunk muscles in healthy adults with people after stroke. Significant differences have been shown in the timing and rate of force development in trunk muscles during movement (Dickstein et al., 2000, Dickstein et al., 2004a, Dickstein et al., 2004b). Trunk muscles have also been shown to be weaker in participants after stroke than in healthy controls (Bohannon et al., 2016, Karatas et al., 2004, Tanaka et al., 1998). While these findings have important clinical implications, these studies didn’t investigate whether these trunk impairments also featured altered alignment.

These findings overall do provide some insight into how trunk muscle performance and upper body alignment may be altered after ABI but are insufficient to answer the question of whether better postural alignment relates to better mobility skills after ABI. As it has been shown that a stable, upright trunk is a feature of walking in healthy adults (Cromwell et al., 2001, Krebs et al., 1992, Sartor et al., 1999), this could represent a gap in knowledge of a key biomechanical issue after ABI. Therefore, this systematic review aimed to identify published evidence of a relationship between postural alignment and mobility for adults following acquired brain injury.

3.2 Methods

The protocol for this systematic review was registered with PROSPERO, registration number CRD42015019867, and the review undertaken in accordance with the PRISMA guidelines (Moher et al., 2009). Systematic database searches were completed using Embase, Scopus, MEDLINE, CINAHL, Web of Science, Sportdiscus, and Cochrane (CENTRAL, CDSR, DARE, HTA, EED) in May 2015. Grey literature was searched using Proquest Thesis and Google Scholar. No limitations were set for publication date or language.

The search strategy had strings related to brain injury, postural alignment and mobility. Three researchers designed the search strategies, with input from an academic librarian. MeSH terms were reviewed for developing the search strings, with multiple search terms used to achieve as complete a search output as possible. The search strategy was adapted for the requirements of each database, with the MEDLINE search strategy shown in Figure 3.1. Google Scholar used an abbreviated search string due to the very high number of hits (Figure 3.1). Where the database allowed, the search was limited to adults and humans. Initial search output was screened by one researcher (SJM) for potentially eligible records. Full-text studies were reviewed by two researchers. Inclusion required both researchers to agree on a study being eligible; if consensus was not reached a third researcher was consulted.

MEDLINE search strategy:

Stroke OR cerebrovascular accident OR CVA OR head injur* OR brain injur* OR ABI OR TBI OR diffuse axonal injury OR brain trauma OR brain isch?emia OR intracranial h?emorrhage* OR brain infarct*

AND

Postural alignment OR posture OR postural OR align* OR biomechanic* OR kinematic* OR pathomechanic* OR three-dimensional OR 3D OR trunk

AND

Mobility OR gait OR walk OR walking OR ambulat* OR ambulant OR sitting OR stand OR standing OR sit-to-stand OR stand-to-sit OR transfer* OR running OR jog OR jogging OR dependent ambulation

Google Scholar search strategy:

"head injury" OR "brain injury"

AND

"postural alignment"

AND

mobility OR gait OR walking OR running

Figure 3.1 Database search strategies

Studies were included if they were empirical studies with participants who were adults with ABI, included measures of both postural alignment and mobility, and analysis included a relationship between alignment and mobility. In the event that studies reported collecting postural alignment and mobility data, but reported no analysis of a relationship, authors were contacted to obtain data for calculating this relationship. Postural alignment was defined as the alignment of body segments relative to vertical when upright (Fortin et al., 2011), which for this review needed to include head or thorax. Assessing the position of the thorax using acromion markers was an accepted method. Measurement of the upper body needed to occur directly from the body segments, not extrapolated from force plate data. Mobility was defined as any element of moving from place to place, including sit-to-stand, standing, walking, running. Any type of study design was considered, as it was recognised that the number of publications on this topic was likely to be relatively low and observational studies were most likely to report the variables required. Abstract-only publications were excluded. Included articles were critically appraised independently by two researchers using the Critical Appraisal Skills Program (CASP) cohort study checklist (casp-uk.net), with questions about exposure and follow-up omitted as these were not relevant to this review, creating a score out of 11. Data extraction was performed by each researcher using a customised spreadsheet.

3.3 Results

Total search output prior to searching Google Scholar was 10657 titles; duplicates were removed using Endnote software leaving 6469 titles. Duplicate titles from Google Scholar were not removed due to the difficulty to export the titles into Endnote from this database; leaving 6872 titles for review (see Figure 3.2). 94 articles were short-listed for full-text review. Of these, 15 studies reported at least one measure of postural alignment and at least one measure of mobility. Four of these had reported on the relationship between those measures, and one other had reported individual participant data that allowed the relationship to be calculated. Authors of the remaining 10 studies were contacted to see if data was available to allow for calculation of the relationship. Data was provided from two of these studies, and the remaining eight studies were excluded due to the lack of data regarding the relationship between postural alignment and mobility (Duclos et al., 2008, Kairy, 2002, Lecours et al., 2008, Lamontagne et al., 2005, Lamontagne and Fung, 2009, Mah et al., 1999, Sousa et al., 2011, Kao et al., 2014). Reference lists of all 15 articles were checked, with no further eligible studies identified.

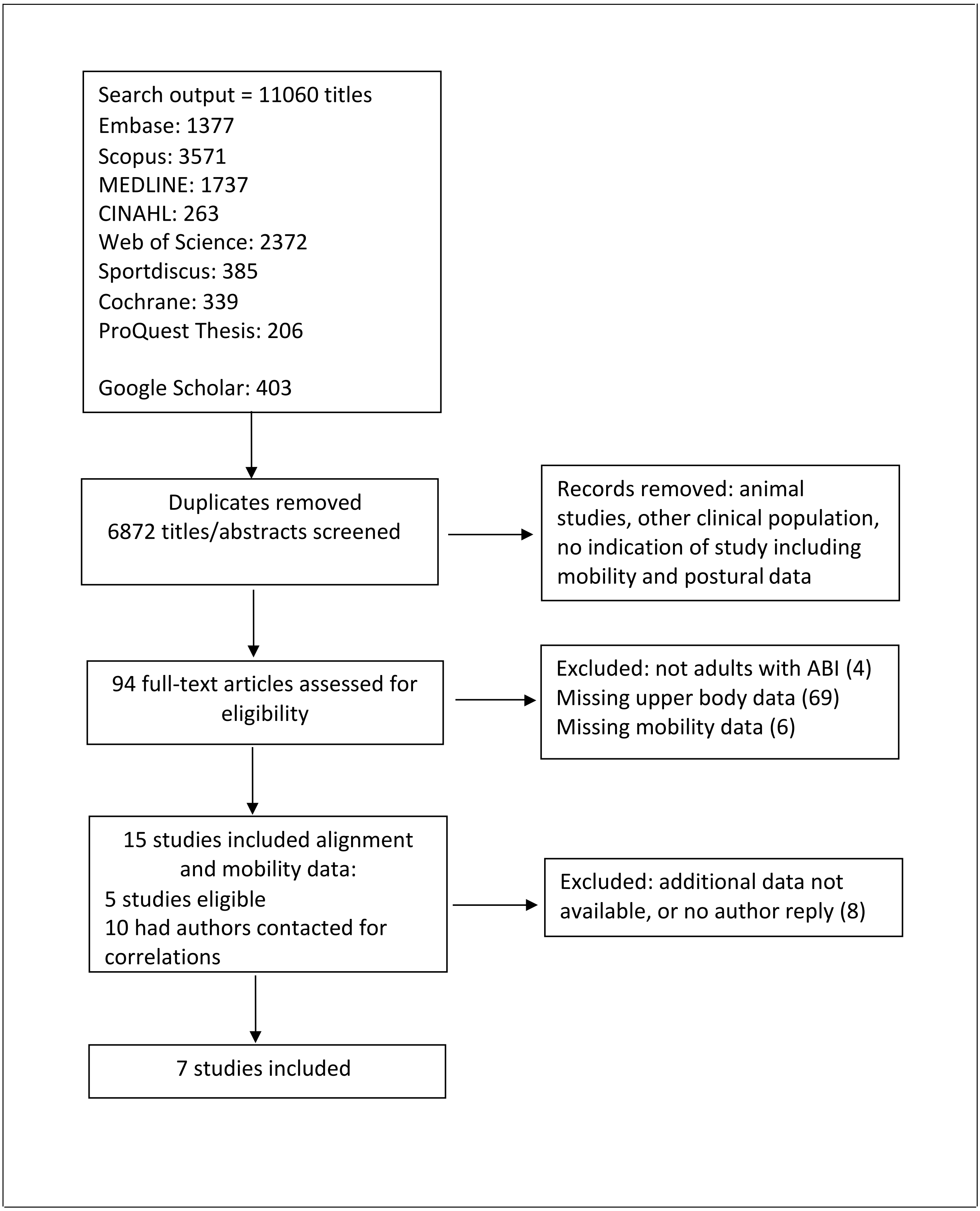


Figure 3.2 Flow diagram of search process

3.3.1 Assessment of studies

All seven included studies were observational; five of these included comparison with a healthy sample. CASP scores were generally high and ranged from 8/11 to 11/11. For the studies that did not score 11/11, the criteria that were not met were method of sampling (used convenience sampling, or not stated), and identification/management of confounding factors. Following appraisal of the studies, all were confirmed for inclusion in the final review. It was noteworthy that none of the studies' primary aim was to investigate the relationship between postural alignment and mobility. Most studies collected and analysed a range of data; only the data relating to this systematic review's question is reported here.

3.3.2 Participant characteristics

A summary of the included studies is presented in Table 3.1, with participant characteristics for each study. Five of the studies investigated people with stroke, and two investigated people with traumatic brain injury. Reported age ranges in the participants with stroke were 37-78. Reported age range in the participants with TBI was younger, ranging from 17-54. It was decided that the studies including 17 year olds would be included in this review of adult evidence, as all participants were participating in an adult rehabilitation service. The samples of participants with stroke had approximately twice as many males as females, whereas the combined samples of participants with TBI had 78% males. All studies of participants with stroke reported participants to be in the chronic phase after stroke, with many participants several years post-stroke. The participants with TBI were also commonly several years post-injury; some were earlier with the shortest time since injury 38 days.

3.3.3 Assessment of postural alignment

Postural alignment measures are shown in Table 3.1. Of the seven studies, six used retroreflective markers in a Biomechanics Laboratory to assess alignment of the trunk during walking; none reported head alignment. Location of markers to calculate trunk position varied between studies, with C7, T2, T10, bilateral acromions and sternum all used. The studies varied in which aspects of trunk alignment were analysed. Two studies examined flexion and lateral flexion of the trunk during walking or running (Williams et al., 2009b, Williams et al., 2013a), using markers on T2, T10 and sternal notch. Two studied lateral displacement of the trunk during treadmill walking (De Bujanda et al., 2004, De

Bujanda et al., 2003), measured as distance of C7 marker lateral displacement, rather than as angle of trunk lateral flexion. One study examined trunk flexion and rotation during overground walking, using acromion and ASIS markers (Egan, 2015). One study examined thoracic rotation during treadmill walking, using bilateral acromion and midsternum markers (Hacmon et al., 2012). The remaining stroke study used a SpinalMouse (Verheyden et al., 2014) which is a mechanical device rolled over the paravertebral region between C7 and S3 vertebrae, to gauge seated and standing vertebral alignment in flexion/extension.

3.3.4 Assessment of mobility

Mobility measures are also shown in Table 3.1. Three of the studies of participants with stroke used treadmill walking to assess walking speed (De Bujanda et al., 2004, De Bujanda et al., 2003, Hacmon et al., 2012). Other mobility measures used in these studies included the Timed Up and Go, timed stairs, Functional Gait Assessment, and BesTest 6. One study of participants with stroke used step length and stride length with and without a walker as the only measures of mobility (Egan, 2015). The remaining study of participants with stroke did not use a specific mobility score, it used the Barthel Index which includes 3 items of mobility (ambulation, stairs and transfers) in its 10 items, and Berg Balance Scale (Verheyden et al., 2014). The studies of participants with TBI used the High Level Mobility Assessment Tool (HiMAT), and walking and running velocities (Williams et al., 2009b, Williams et al., 2013a).

Table 3.1 Overview of studies included in review

Study	Participants	Age	Alignment measures	Mobility measures	Correlation coefficients (statistically significant r values shown in bold)					CASP Declaration of funding
De Bujanda et al. (2003)	Chronic stroke, n = 10 1 female, 9 male Mean time since stroke 69 (±26) months	Mean age 57.7; range 37 - 65	C7 mean lateral displacement during treadmill walk (2D)	Natural walking speed on treadmill Maximal walking speed on treadmill Stairs per minute Timed Up & Go		*C7 lateral displacement (nat speed)*	*C7 lateral displacement (max speed)*			9/11 Researchers supported by a scholarship from FRSQ and salary support from CIHR.
					TUG	**0.68***	**0.71***			
					Climbing stairs	**-0.72***	**-0.77***			
					Nat Walk Speed	**-0.79***	**-0.75***			
					Max Walk Speed	**-0.75***	**-0.66***			
De Bujanda et al. (2004)	Chronic stroke, n = 10 1 female, 9 male Mean time since stroke 69 (±26) months	Mean age 57.7, range 37 - 65	C7 mean lateral displacement during treadmill walk (2D)	Natural walking speed on treadmill	C7 displacement & Natural walking speed: r = -0.52					11/11 Financial support from FRSQ and CIHR.
Egan (2015)	Stroke n=5 1 female, 3 male, 1 not stated Time since stroke stated only as subacute	Age range 43-78	Trunk flexion, trunk rotation during overground walking with and without walker: markers on acromions and ASIS	Step length and stride length during walking, with and without walker		*Trunk rot with*	*Trunk rot without*	*Trunk flexion with*	*Trunk flexion without*	8/11 No statement of funding
					Step length with walker	**-.90***		.40		
					Step length without		-.70		-.50	
					R stride length with walker	-.50		.50		
					R stride length without		-.70		-.50	
					L stride length with walker	**-.90***		.40		
					L stride length without		-.70		-.50	

Hacmon et al. (2012)	Chronic stroke n=11 3 female, 8 male Mean time since stroke 32 (±26) months	Mean age 62 years (±11)	Range of thoracic rotation during one stride of treadmill walk: markers on acromions and midsternum	Functional Gait Assessment BesTest 6 (Gait Stability)	Thoracic rotation & FGA: **r = −0.54 *** Thoracic rotation & BesTest 6: **r = −0.63 ***			10/11 Study partially supported by the CIHR. Researcher supported by HSFC and the Physiotherapy Foundation of Canada.
Verheyden et al. (2014)	Chronic stroke n=21 9 female, 12 male Mean time since stroke 7 years (±6.6)	Age 67 (±10)	Trunk inclination using SpinalMouse in comfortable upright posture	Berg Balance Scale Barthel Index	Standing trunk inclination & BBS: **r = −0.64*** Standing trunk inclination & BI: r = −0.51 Seated trunk inclination & BBS: r = −0.15 Seated trunk inclination & BI: r = 0.10			10/11 The authors declare no source of funding.
Williams et al. (2009b)	TBI n=41 11 female, 30 male n=28 of these included alignment data	Mean age 29.1 years, range 17–54	Mean trunk flexion, mean trunk lateral flexion during overground walking: markers on T2, T10, sternal notch	HiMAT Self-selected walking velocity		*Trunk flexion*	*Trunk lateral flexion*	10/11 Supported by the Victorian Neurotrauma Initiative and RACV.
					Walking velocity	0.365	**0.49****	
					HiMAT	0.271	**0.39***	
Williams et al. (2013a)	TBI n=44 8 female, 36 male	Age range 17–54	Mean trunk flexion, mean trunk lateral flexion during overground running: markers on T2, T10, sternal notch	HiMAT Self-selected running velocity		*Trunk flexion*	*Trunk lateral flexion*	8/11 Supported by a fellowship from the Victorian Neurotrauma Initiative
					Running velocity	-0.001	0.021	
					HiMAT	0.255	0.173	

*****p<0.05 ******p<0.01 2D = two dimensional; (±) = standard deviation; FGA = Functional Gait Assessment; ASIS = anterior superior iliac spine; BBS = Berg Balance Scale
BI = Barthel Index; HiMAT = High Level Mobility Assessment Tool; TBI = Traumatic Brain Injury; FRSQ = Fonds de la recherche en sante´ du Que´bec
CIHR = Canadian Institute of Health Research; HSFC = Heart and Stroke Foundation of Canada; RACV = Royal Automobile Club Victoria

3.3.5 Relationship between alignment and mobility

These results are summarised, and correlation values provided, in Table 3.1. De Bujanda et al. (2003) evaluated lateral trunk displacement during treadmill walking after stroke, and reported that better scores on the four mobility tests were significantly correlated with lesser lateral trunk displacement. De Bujanda et al. (2004), appearing to use the same sample as the previous study, reported that the relationship between lesser lateral trunk displacement and faster natural walking speed on a treadmill was not statistically significant. In the study by Egan (2015), the two correlations that achieved statistical significance were trunk rotation correlating with step length with walker and with left stride length with walker. None of the correlations were statistically significant when walking without a walker. The study by Hacmon et al. (2012) of treadmill walking in people after stroke, reported that greater thoracic rotation during treadmill walking correlated with lower scores on Functional Gait Assessment and BesTest 6, with these relationships statistically significant. Verheyden et al. (2014) reported that forward inclination of the trunk in standing tended to correlate with lower scores on clinical measures. Negative correlation between trunk flexion and Berg Balance score was statistically significant, whereas the relationship did not achieve significance for Barthel Index. Correlations between sitting posture and mobility measures were much lower and were not statistically significant. Williams et al. (2009b) reported significant correlations between both walking speed and HiMAT score with trunk lateral flexion after TBI. Correlations between these mobility scores and trunk flexion were not statistically significant. Williams et al. (2013a) examined running speed and HiMAT after TBI, and reported non-significant correlations between these scores and both trunk flexion and lateral flexion.

Comparing results between studies, we attempted to pool data from studies with similar methods. Although three studies reported on both lateral trunk displacement and walking velocity (De Bujanda et al., 2004, De Bujanda et al., 2003, Williams et al., 2009b), the methods used to measure postural alignment were not similar enough to combine them for meta-regression.

3.4 Discussion

Results of this systematic review indicate that the relationship between postural alignment and mobility skills after ABI is not clear. Published evidence has not established whether better postural alignment either is or is not correlated with more advanced mobility skills after ABI. The low number of eligible studies, the varied measures of mobility and postural alignment used, the lack of consistency in relationships calculated in the included studies, and the generally small sample sizes provides for limited insight into this relationship.

This review has also demonstrated that postural alignment is typically absent from biomechanical research into mobility after ABI. Only a tiny proportion of the mobility studies screened in this systematic review investigated any alignment of the upper body. It was noted that some studies that collected data on the upper body did not report it, and had not included the upper body in their planned analysis. The included studies also did not focus on postural alignment being a factor to influence mobility skills – the correlations reviewed here were often not part of the aims of the studies. Three of the included studies had not reported a correlation between their postural alignment and mobility scores; calculations from provided data were made for the purpose of this systematic review.

Five of the seven studies demonstrated one or more statistically significant correlations between an alignment measure and a mobility measure (Table 3.1). The significant correlations in the studies of participants with stroke supported a more stable, upright trunk correlating with better mobility. The trend was different in participants with TBI (Williams et al., 2009b), where better mobility scores were correlated with greater trunk lateral flexion during walking. Correlations with trunk flexion were not statistically significant. Understanding the variation in these findings would be aided by greater understanding of postural alignment in healthy adults and how it differs after brain injury. The variation in measures used to evaluate alignment in the included studies may indicate that optimal methods for measurement need further determination, but also that the aspects of upper body alignment that are most significant to mobility performance are not yet understood. There were also marked differences in methods used to measure mobility. Walking was the most frequently evaluated aspect of mobility in the studies included in this review. Three studies evaluated walking solely on a treadmill, which has previously been found to alter overground kinematics of walking after stroke (Brouwer et al., 2009, Harris-Love et al., 2001). In the study by Egan (2015) only stride and step length were measured to represent walking performance, providing a limited rating of walking skills. This study also did not report whether trunk flexion measures were peak trunk flexion, average, or another parameter, which makes interpretation more difficult. Egan (2015) reported that two of the five participants had a statistically significant decrease in trunk flexion with walker compared to walking without, indicating participants may have compensated for a lack of postural extension by propping themselves with their arms. The other three participants had no significant difference with and without the walker. Verheyden et al. (2014) did not include a pure mobility measure in their study of people with stroke, potentially limiting the application of their findings to pure mobility skills.

Evidence exists for multiple aspects of motor training to improve mobility and this is a core area for rehabilitation (Tyson and Connell, 2009). The search undertaken for this systematic review has demonstrated that despite a huge volume of kinematic research into mobility after brain injury, a whole-body understanding of kinematics of mobility skills such as walking is lacking. There is a dearth of evidence relating to the upper body and postural alignment, leaving a question about whether there are similar gaps in clinical practice. The majority of body mass lies in the upper body, with two thirds of body mass lying two thirds of body height above the ground (Winter, 1995). From this simple biomechanical perspective, the upper body appears too important to ignore.

Trunk muscle training has received increasing attention in recent research in neurological rehabilitation, with multiple randomised controlled trials published. Sorinola et al. (2014) reported in their meta-analysis of additional trunk exercises for people after stroke that trunk exercises in sitting and lying significantly improved standing balance and mobility scores early after stroke. Cabanas-Valdes et al. (2013) reported in their systematic review of trunk training in people after stroke that sitting balance scores and Trunk Impairment Scale scores tended to improve in the trunk exercises groups. None of the studies included in these reviews used a measure of postural alignment, although one used a measure that had reference to upright posture (de Seze et al., 2001).

While specific motor impairments and postural alignment have each been researched after brain injury, these have not tended to be evaluated together. The study by De Bujanda et al. (2003) reported that decreased lateral control of the trunk correlated with reduced walking capacity on a treadmill after stroke. This study correlated lateral trunk displacement with other variables including Chedoke McMaster leg and foot scores but didn't measure muscle performance of the trunk or pelvis, so it wasn't apparent what motor impairment was most related to the degree of trunk displacement. Studying sit-to-stand mechanics, Mazza et al. (2006) reported that greater extension of head and torso during sit-to-stand after stroke related to improved performance. They measured muscle strength in these participants, but only of leg muscles, so it wasn't apparent whether trunk muscle strength was related to the mechanics of the upper body. Despite the growth in research of trunk muscle performance, it does not seem clear which motor factors most influence postural alignment.

There are few clinical measurement tools available to rate posture in neurological populations (Tyson, 2003), and none of the included studies used one. Use of a validated clinical tool could have allowed for meta-analysis of results, and also could assist with application of results to clinical practice. In a systematic review of tools to measure posture, it was recommended that a new measurement tool would need to be developed to meet requirements for clinical utility in stroke rehabilitation (Tyson, 2003). While there are measurement tools for walking that include posture, these were not used in any of the studies included in this review. A systematic review of observational analysis scales for assessing walking after stroke showed that four of five eligible scales included the upper body as part of global walking analysis (Ferrarello et al., 2013). The scales including the upper body were the Rivermead Visual Gait Assessment (Lord et al., 1998), Gait Assessment and Intervention Tool (Daly et al., 2009), Hemiplegic Gait Analysis Form (Hughes and Bell, 1994) and New York Medical School Orthotic Gait Analysis (Goodkin and Diller, 1973), whereas the Wisconsin Gait Scale (Pizzi et al., 2007) does not include the upper body. While this demonstrates that options are available for clinicians to include upper body quantitative measurement, these scales may not be commonly used. There are multiple factors that could affect uptake of a measurement tool including clinicians' perception of relevance and applicability, time required, precision and usefulness of the information provided by the measure (Hillier et al., 2010, Salbach et al., 2011). The lack of research publications including upper body posture may be a factor limiting clinical uptake of the tools that include it. The limited number of tools for clinicians to evaluate posture could also contribute to it being neglected in clinical assessment. The term “lower limb function” is commonly used to refer to walking (Cooke et al., 2010, Pollock et al., 2007), which may also limit recognition of walking as a whole-body activity.

Three-dimensional kinematic analysis of walking has been shown to be generally highly reliable in a systematic review (McGinley et al., 2009), although it is illustrative that there was no upper body data reported from any of the included studies in the review. 3D kinematic analysis has been recommended over observational analysis based on degree of observer accuracy (Williams et al., 2009a), although like all measurement tools 3D kinematic analysis has its own strengths and limitations. A key strength is that any body segment can be included, and most studies included in the present systematic review used 3D kinematic analysis to observe and rate one or more aspects of postural alignment of the upper body. However, the facilities, skills and time required for this are not available to all clinicians, so other means of analysis and measurement are also required for clinical practice and research. Options for analysis of posture in musculoskeletal practice have been described in a systematic review; the methods listed were photography, goniometry, inclinometry, tape measurement, and use of a flexible device to measure spinal curves (Fortin et al., 2011). Measurement of body angles from photographs was described as likely to be the most quick and accurate method clinically. Photogrammetry has also been used for measurement of different aspects of posture following stroke (Iyengar et al., 2014), so could offer an achievable two-dimensional option.

Motor performance of the trunk has been included in development of several measurement tools in the brain injury field. Tools rating trunk performance have commonly included items such as rolling, sitting balance and lie-to-sit (Collin and Wade, 1990, Fujiwara et al., 2004, Montecchi et al., 2013, Verheyden et al., 2004, Benaim et al., 1999). In reviewing these measurement tools it is apparent that posture has not been a focus of analysing motor performance of the trunk, despite posture being a key role of trunk muscles. There is an opportunity to expand the scope of clinical assessment and clinical research to include the upper body during mobility more consistently. However, it is yet to be established how significant postural skills are relative to the skills currently included in trunk-related scales.

Many people live with marked limitations in mobility for years after surviving a brain injury (Hillier et al., 1997, Tate et al., 2012). It is important that clinicians and researchers continue to seek means of improving outcomes, and progressing evaluation and training of mobility skills is an important component. The gaps in evidence may be greater for populations with severe physical impairment after ABI (Lubetzky-Vilnai and Kartin, 2010). Severity of physical impairment can be a factor that precludes some people from being provided with rehabilitation services after ABI (Lynch et al., 2015), so for severely impaired groups the need to develop improved methods of assessment and intervention may be even more critical. It is noteworthy that each of the participant groups included in this review were independent with mobility. Biomechanical research has commonly focussed on people who are independent with walking after ABI, so less is known about biomechanics of mobility for those who aren't independently ambulant. From included studies in this review, trunk flexion during independent running was not found to be significantly different between TBI and healthy samples (Williams et al., 2013a), whereas greater trunk flexion during independent walking was observed after TBI (Williams et al., 2009b). It was hypothesised by the authors that an upright trunk may be a requirement to achieve running after TBI, which may indicate that postural skills are important for advancing mobility performance. However, this does not identify the importance of postural skills for those who need assistance to walk after ABI. A study of adults after stroke comparing kinematics of walking with different walking aids found no difference in kinematics using the different aids. It showed that more symmetrical and stable pelvic motion correlated with faster walking speed, but did not include data from body segments above the pelvis, so postural performance was unknown (Tyson, 1999). A novel kinematic study of adults with ABI who needed assistance to walk found clinically useful differences in walking under different training conditions, but did not report data on upper body alignment (Williams et al., 2011). It did demonstrate that the mode of assistance influenced walking parameters, which has implications for rehabilitation professionals who train walking. While the need for more knowledge of postural alignment during mobility applies to ambulant and non-ambulant groups with ABI, there is a particular need for greater knowledge about optimising mobility outcomes for those who lack independence.

3.5 Implications

There is limited evidence that a more stable, upright trunk is associated with better walking after ABI, and other evidence that found the opposite or ambiguous results. While the review has not identified adequate evidence to demonstrate the strength of the relationship between postural alignment and mobility, there is no indication that the upper body should be excluded from analysis of mobility after ABI. There is a suggestion for clinicians that it may be worthwhile to include posture when evaluating mobility.

There is also an implication for clinical research; the upper body is relevant to consider when investigating kinematics of mobility after ABI. There is a clear need for more research studies to gather and analyse data on the upper body during mobility. Larger studies with methods that allow for pooling of data are needed to provide more generalisable findings.

3.6 Limitations

This review identified a low number of studies relevant to the research question. Publication bias could not be statistically assessed due to having fewer than 10 included studies.

3.7 Conclusion

Evaluation of postural alignment during mobility for adults after ABI is lacking in published research. The evidence that exists is insufficient to answer the question of how much postural alignment relates to mobility after ABI.

3.8 Recent advances in evidence

Screening the ABI literature and repeating the searches in MEDLINE and Google Scholar for new evidence of a relationship between postural alignment and mobility identified two relevant studies.

Katsuhira et al. (2018) compared wearing a trunk orthosis with a corset to influence walking parameters in adults using a hemiplegic ankle orthosis after stroke. Use of the trunk orthosis decreased lateral deviations and inclination of the trunk, compared to the group wearing a corset. For example, the median value of peak forward bending of the trunk in stance phase was reported as 5.62° without the orthosis, and 1.60° with the trunk orthosis. The group wearing the trunk orthosis were also significantly different from the corset group for some walking parameters, including faster walking speed and increase in paretic steps per minute, although relationships between alignment and walking measures were not reported. When comparing the trunk orthosis and corset groups to baseline measures wearing only the ankle orthosis, the trunk orthosis group improved walking parameters significantly whereas the corset group did not. It appeared that stabilising the trunk in a more upright position may have positively influenced some walking parameters.

Hefter and Rosenthal (2017) investigated the effect of botulinum toxin injections into the arm after stroke on walking parameters including trunk deviations. There were significant improvements in trunk alignment towards midline and increased walking speed, although the association between these two was not reported. This study provides a demonstration of the whole-body nature of kinematics, as an intervention to the arm caused changes to both trunk alignment and walking. Further research investigating how arm position influences postural alignment may be valuable.

These studies add to the evidence indicating that there is a relationship between postural alignment and mobility after ABI. While most studies included in the systematic review were not actually investigating postural alignment, it was the focus for these more recent studies, which may reflect an emerging theme in the literature. The methods to measure alignment and mobility have continued to vary in these publications. Still no studies have been found to investigate the relationship between alignment and mobility in people who are non-ambulant after ABI.

The authors were contacted to see if data were available to allow for calculation of the correlations between alignment and mobility measures, with no response received.

Table 3.2 Overview of additional studies

Study	Participants	Age	Alignment measures	Mobility measures	Correlation coefficients	CASP Declaration of funding
Katsuhira 2018	Chronic stroke n = 27	Mean age 69.9; range 57 - 84	Thorax angle sagittal Thorax angle frontal	Walk speed Paretic steps / min	Not available	6/11 Japan Society for the Promotion of Science
Hefter 2017	Chronic stroke n = 15	Mean age 65.8; range 47 – 78	Upper trunk lateral flexion Upper trunk forward flexion	Preferred walk speed	Not available	8/11 Co-funded by the German federal state North RhineWestphalia and the European Union

Chapter 4

Postural alignment is impaired in sitting and standing after complex acquired brain injury: an observational study

This manuscript has been prepared for submission to Archives of Physical Medicine and Rehabilitation:

Mills SJ, McDonnell MN, Mackintosh S, Thewlis D: Postural alignment is impaired in sitting and standing after complex acquired brain injury: an observational study

Abstract

Objectives: To investigate if postural alignment differs between healthy adults and adults with acquired brain injury (ABI). Establish validity and repeatability of a new kinematic method for measuring postural alignment relative to the base of support.

Design: Observational study.

Setting: Inpatient rehabilitation centre and university research laboratory.

Participants: 14 adults with ABI who were non-ambulant at eight weeks post-injury and 14 healthy adults.

Methods: Kinematic data were recorded using motion capture technology in sitting and standing while holding rails, to allow inclusion of people with severe impairment, and without rails when able. Testing was repeated on a second day to evaluate repeatability. Postural alignment of each sample was graphed, displaying body segment positions in the transverse plane. A new Postural Alignment and Dispersion (PAD) score was developed, quantifying average body segment displacements from the base of support in the transverse plane. The PAD score was evaluated for construct validity by correlating scores with clinical alignment rankings of adults with ABI.

Results: Greater postural alignment deviations were observed in participants with ABI. Mean alignment scores varied between conditions and samples, range 0.027 – 0.105. PAD scores correlated with the clinical alignment rankings (ρ=0.673, p=0.023). Intraclass correlation coefficients (ICC) for scores between days indicated moderate to excellent repeatability for the four conditions in healthy adults; range 0.701 to 0.945; minimal detectable change (MDC) range 0.003 - 0.019. For adults with ABI, ICC for conditions with sufficient data also indicated moderate to excellent repeatability, range 0.614 - 0.912; MDC range 0.016 – 0.045.

Conclusions: Postural alignment relative to the base of support can change after ABI. Construct validity of PAD score measurement of postural alignment was shown. Repeatable kinematic measurement of whole-body postural alignment can be applied to people with complex impairments after ABI.

4.1 Introduction

Upright postural alignment of the head and trunk is a fundamental skill for human function (Sanchez et al., 2017, Cromwell et al., 2001, Kavanagh et al., 2006). Humans are typically highly accurate when gauging their vertical position in sitting, suggesting that the neuromuscular system prioritises upright alignment (Conceicao et al., 2018). Aspects of postural alignment can be significantly impaired after acquired brain injury (ABI) in sitting, standing and walking (Williams et al., 2009b, Verheyden et al., 2014, Conceicao et al., 2018). Despite this, there has been little investigation into whole-body postural alignment after ABI, or how postural impairment relates to physical function (Mills et al., 2017).

Posture has been measured using varied methods, although the optimal measure is not clear (Claeys et al., 2016). Individual body segment angles of healthy adults have been measured in sitting and standing using kinematic data (Amabile et al., 2016, Krawczky et al., 2014, Fortin et al., 2011). However, in clinical practice, interpreting deviations of individual segments requires an understanding of how the body aligns overall. Postural measures used in clinical studies include displacement of the centre of gravity in sitting and standing, (Lafosse et al., 2007), visual categorisation of trunk tilt in sitting (Taylor et al., 1994) or use of an inclinometer on the trunk and head (Piscicelli et al., 2016). Some studies have analysed in one plane (Bansal et al., 2014, Nair et al., 2015), but complex postural deviations occur in more than one plane (Carozzo et al., 2020, Williams et al., 2009b). Further, studies have often limited participants to those who can stand or walk unsupported, providing little insight into the nature of these issues for people with more severe deficits (Verheyden et al., 2014, Paillex and So, 2005, Perlmutter et al., 2010). Therefore, this study aimed to compare postural alignment in healthy adults with postural alignment in survivors of ABI with severe mobility impairment. It also aimed to develop a valid, repeatable method of measuring whole-body postural alignment, suitable to apply to people with severe impairments. We measured displacement of body segments above the base of support (BoS) in the transverse plane, to enable postural deviations in any direction to be captured.

4.2 Methods

This observational study was approved by the local Human Research Ethics Committees (healthy adults' protocol 33756; adults with ABI 150414). All participants were 18 years old or over and provided written informed consent prior to enrolment in the study, or where they were unable to, a guardian provided written informed consent.

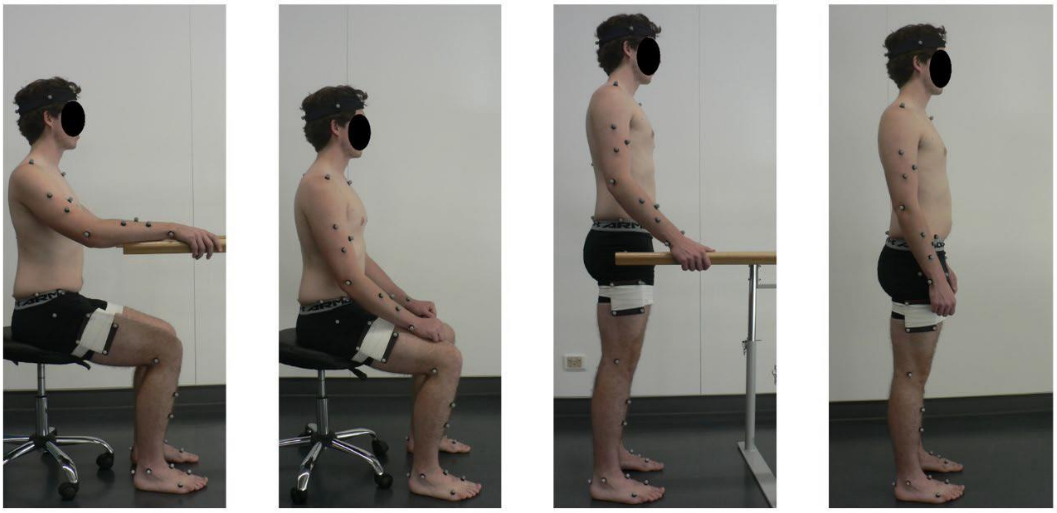
4.2.1 Participants

Healthy Adults: a convenience sample was recruited from advertising at the study site between March and July 2015. Inclusion criteria required having no restrictions with mobility; able to walk over one kilometre easily and hurry down a flight of stairs easily. Exclusion criteria included history of neurological illness, and physical limitations causing difficulty with mobility tasks.

Adults with ABI were recruited from consecutive admissions to inpatient brain injury rehabilitation, between December 2015 and July 2017, within a longitudinal study of postural alignment and mobility recovery. Diagnosis of ABI was confirmed by the medical record. Eligibility required mobility to be severely impaired at eight weeks post-ABI (maximum score of two on items eight and nine of the Clinical Outcome Variables Scale – they were not walking or could walk less than 10 metres requiring at least two assistants). This criterion was selected as anecdotally, impaired postural alignment commonly accompanies severe mobility impairment after ABI. Mobility status at eight weeks post-ABI was selected for eligibility as people who lack independence at 2-3 months post-ABI have been reported to be unlikely to achieve it (Katz et al., 2004, Kwakkel and Kollen, 2013). Participants entered the study when able to manage at least one testing condition, for at least five seconds, which for most participants with ABI was more than eight weeks post-injury. Managing the testing procedure also required the ability to follow the instructions during testing. Exclusion criteria were mobility impairment resulting primarily from issues other than their recent ABI, or diagnosis of progressive neurological disease. For both samples, individuals were excluded if bony landmarks for body markers were unable to be palpated, typically with body mass index greater than 35 kg/m^2.

4.2.2 Experimental protocol

Kinematic data were collected during sitting and standing, each repeated holding parallel bars, for application to patients who rely on external support (Figure 4.1). Seat and rail heights were not normalised to participant anthropometry. For healthy adults, seat height was fixed at 0.54m and parallel bars at 0.90m height. For adults with ABI these were adjusted individually to aid upright posture and balance (seat height range 0.50 – 0.54m, parallel bars range 0.82 – 0.95m). Healthy adults completed all tests; adults with ABI completed those that they could. Participants with ABI were able to wear shoes / orthoses if required, but all chose barefoot. Additionally, participants who were able were also recorded during walking tasks, with all information about walking data collection and results available in Supplementary material. Participants' body mass and height were collected. The STROBE statement was used to guide reporting (Elm et al., 2007).



Left to right: sitting with rails, sitting, standing with rails, standing.

Figure 4.1 Conditions for measurement of postural alignment

Retroreflective markers (14 mm diameter) were positioned bilaterally on anatomical landmarks: 1st and 5th metatarsals, dorsal aspect of the 2nd metatarsals, calcanei, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, anterior superior iliac spines, posterior superior iliac spines, iliac crests, acromion processes, medial and lateral humeral epicondyles, ulnar and radial styloid processes, and on T2 and T10 spinous processes, and jugular notch. In addition, clusters of three (arms) and four (legs) markers were attached to the upper arms, forearms, thighs, and shanks, and four markers were attached to a headband worn at the level of the forehead (Figure 4.2). Marker locations were based on the protocol from Cappozzo et al. (1995), and the trunk locations were based on Leardini et al. (2013), which was varied by use of T10 instead of than the midpoint of the scapular inferior angles. A static anatomical calibration file was recorded for each participant, each session, in sitting if not able to stand. Three trials up to 30 seconds were recorded for each sitting and standing task. For standing, participants were instructed to have feet level, with assistance provided to position feet if required. Participants were asked to sit and stand remaining “as tall and even as you can”. All participants repeated testing on a second day for evaluating repeatability: healthy adults mean gap 17 days (range 7 – 28 days); adults with ABI had less time between testing days due to potential for change, mean 2 days (range 1 – 7 days).

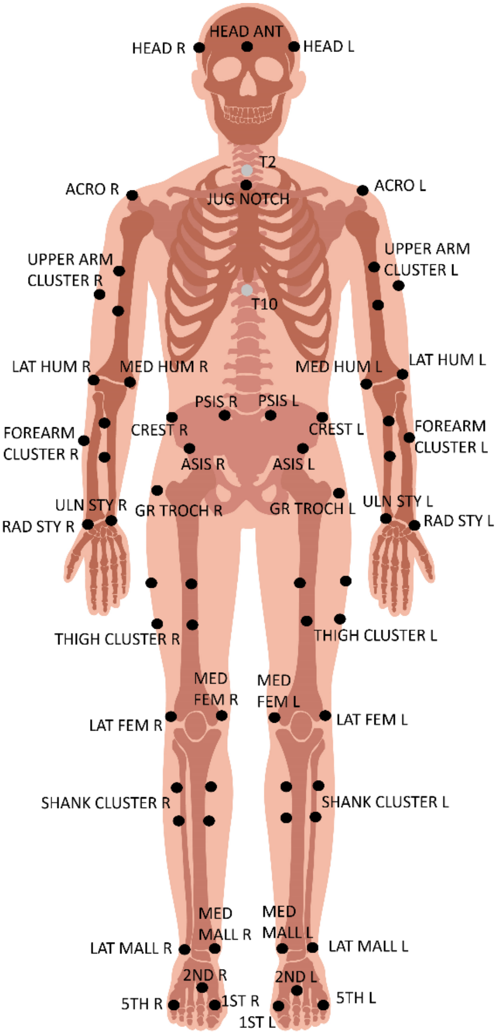


Figure 4.2 Marker set. Markers on calcanei and back of head not shown.

4.2.3 Data collection and kinematic model

For healthy adults, kinematic data were collected using a 12 camera Vicon MX-F20 motion capture system (Vicon Motion Systems, Oxford Metrics, Oxford, UK) at 100 Hz, and marker trajectories reconstructed and labelled in Vicon Nexus (v1.8.5). For the adults with ABI, 12 Optitrack cameras and AMASS software (C-Motion, Inc., USA) were used, which have been shown to be comparably accurate to Vicon (Thewlis et al., 2013). All data were exported to Visual3D (C-Motion, Inc., USA) in .c3d format for post-processing, and were filtered using a 4th order low pass Butterworth filter with a cut off frequency of 6 Hz. From the marker trajectories, body segments were defined by anatomical coordinate systems (Cappozzo et al., 1995), and modelled with six degrees of freedom: head, thorax, pelvis, thighs, lower legs, and feet. The arms were excluded, to prioritise axial and leg segments' alignment over the BoS. The model's segment parameters, i.e. mass, mass moments of inertia and centre of mass (CoM) position, were scaled using the regression coefficients from de Leva (de Leva, 1996). For each task, a BoS coordinate system was established (Figure 4.3). For sitting, the pelvis defined the BoS. For standing, the BoS was defined by the feet, as a box, with the ends of the box defined as two vectors intersecting the calcaneal markers and the distal end of each foot. The length vector was defined as the intersection of the two end vectors at 50% of their length. The width of the BoS was defined as the distance between the 5th metatarsal markers. BoS coordinate systems were defined using the right-hand rule where the y-axis was defined by the length vector and the x-axis was defined as the width vector. The z-axis was calculated as the cross product of the x- and y- axes. The origins of the coordinate systems were transformed to 50% along the y-axis length. The CoM coordinates for all body segments above the BoS coordinate system (sitting: head and thorax; standing: every segment excluding the feet) were exported to MATLAB (2018a, Mathworks, USA) for processing using custom-written code. The median segment CoM positions were exported for each condition. An individual graph of transverse plane body segment positions was exported for each condition completed by each participant, for error-checking of outlying data.

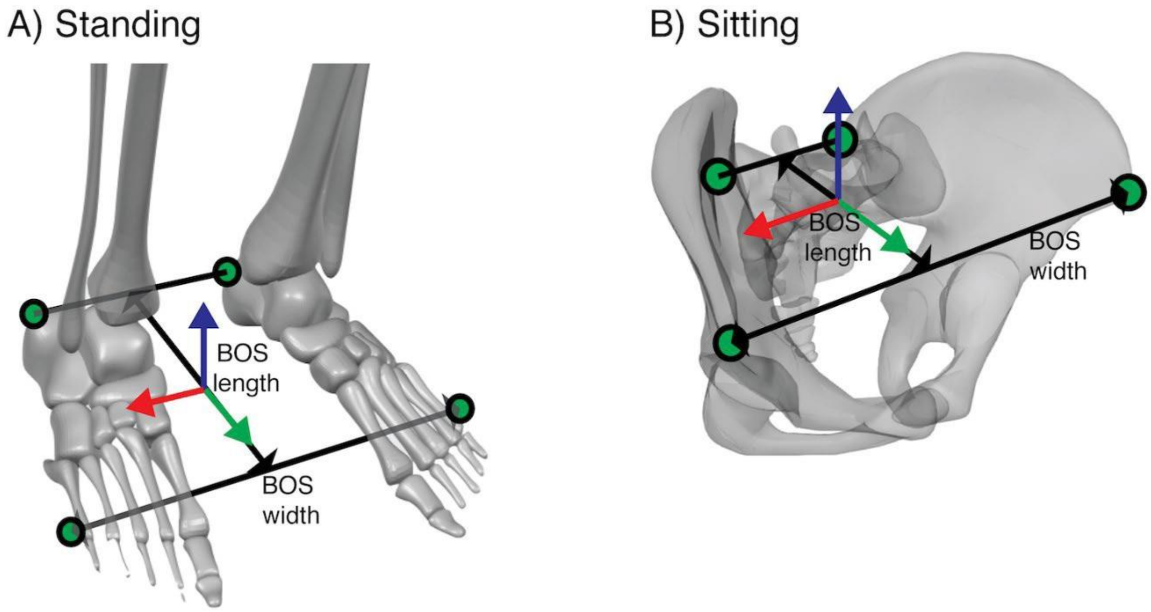
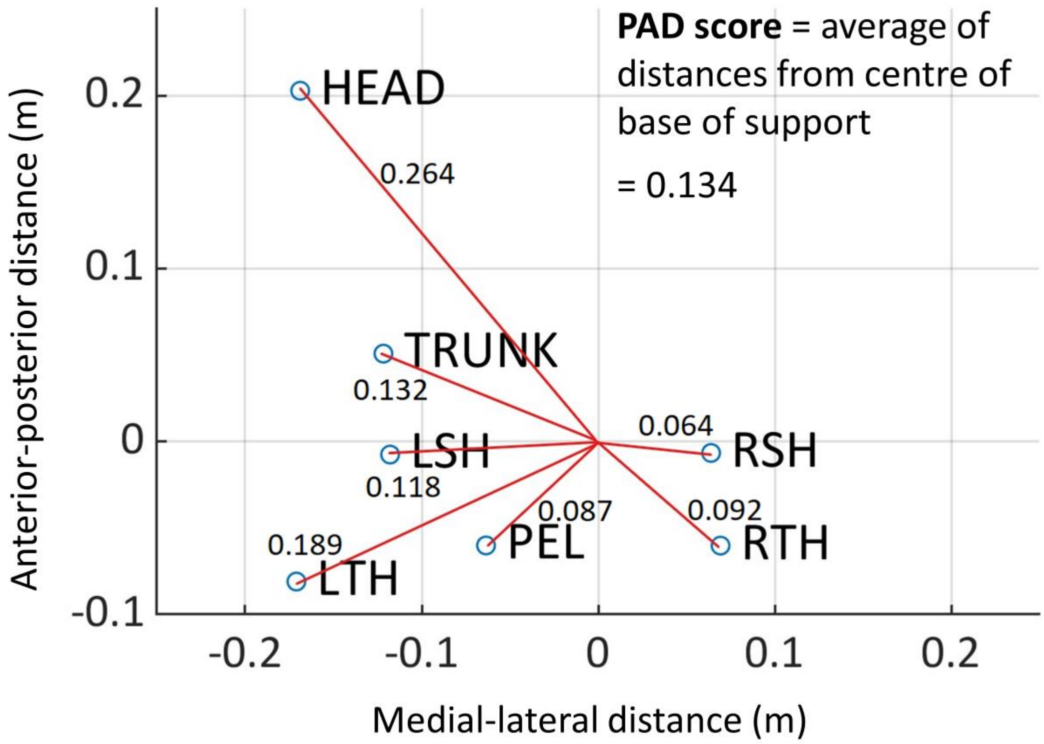


Figure 4.3 Base of support coordinate systems

4.2.4 Data reduction

Postural alignment was defined as the alignment of body segments relative to each other when upright (Fortin et al., 2011). To generate the Postural Alignment and Dispersion (PAD) score, the segments' CoM coordinates in the xy (transverse) plane were expressed relative to the BoS coordinate system. Participants had varied stance widths in standing, so the X-axis data for all standing segments was normalised by dividing by the proportion of their stance width to the median stance width for each sample (0.34m). The PAD score was calculated using the segments above the BoS, as the sum of these segments' transverse plane distances from the centre of the BoS, divided by the number of segments (Figure 4.4).



LTH = Left thigh; LSH = Left shank; PEL = Pelvis;
RTH = Right thigh; RSH = Right shank

Figure 4.4 Example of PAD score calculation, shown on graph of body segment positions

4.2.5 Data analysis

Descriptive, parametric and non-parametric tests were run in SPSS (IBM statistics, Version 25). Normality of distributions was assessed using Shapiro-Wilk tests and histograms. To evaluate construct validity of the PAD score, the Spearman correlation between PAD scores and clinical rankings of postural alignment was calculated. The three physiotherapist investigators (SJM, MNM, SM, each with greater than 15 years' experience working with neurological patients) collaboratively ranked alignment of participants with ABI who could stand holding rails (n=11), using recorded images in sagittal and coronal views. This resulted in a ranking order of one (best) to eleven (worst). Healthy adults' photos were used as comparators to inform the rankings. Graphs of transverse plane segment positions were constructed in MATLAB for each condition, for visual representation of body segment dispersion. Independent samples t-tests and Mann- Whitney U tests assessed for statistical differences between the samples' PAD scores. For inter-session repeatability of postural scores, intraclass correlation coefficients ($ICC_{3,1}$) were calculated. ICCs of 0.5 to 0.74 were considered moderate, 0.75 to 0.89 considered good and 0.9 or over considered excellent

(Portney and Watkins, 2015). Paired t-tests and Wilcoxon signed rank tests assessed for differences between session means for each sample's PAD scores. Results were considered significant with $p \leq 0.05$. Bland Altman plots were constructed for each condition in MATLAB to check for a proportional bias of scores above or below the mean difference between sessions.

4.3 Results

Fourteen healthy adults (nine men, five women) were included. Mean age was 26 years (range 18-61 years), mean height 1.74 m (range 1.63-1.87 m), mean mass 65 kg (range 47-81 kg). From 252 consecutive admissions to ABI rehabilitation, 32 met the mobility impairment criterion. Of these, exclusions were due to: inability to follow instructions adequately or achieve any testing condition (n=8); inability to participate due to medical issues, nausea or fatigue (n=5); or bony landmarks unable to be located (n=3). One eligible adult declined. Fifteen adults with ABI entered the study; one was unable to adequately follow instructions at the first session and was withdrawn, therefore fourteen adults with ABI were included (seven men, seven women). Mean age was 43 years (range 20-75 years), mean height 1.70 m (range 1.55-1.82 m), mean mass 65 kg (range 50-105 kg). All participants were less than one year post-ABI at baseline. PAD score descriptive statistics and missing data are shown (Table 4.1).

4.3.1 Construct validity

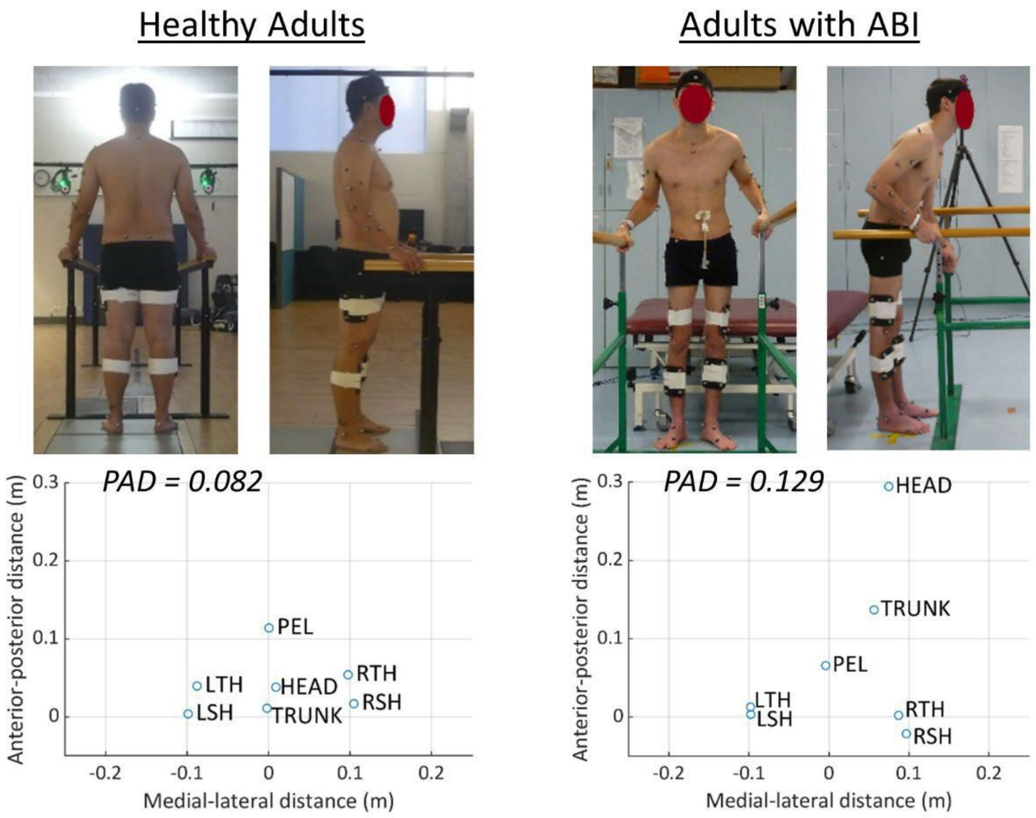
Positive correlation between PAD scores and the clinical rankings was statistically significant (ρ=0.673, p=0.023). Examples of sagittal and frontal photos are shown with PAD scores and transverse plane body segment position graphs (Figure 4.5).

4.3.2 Comparing postural alignment in participants with and without ABI Healthy adults' body segment dispersion graphs showed the head, thorax and pelvis aligned closely, consistent with upright posture (Figure 4.6). They appeared consistently close to midline on the x-axis in sitting and standing conditions, and in standing thighs and shanks were spaced evenly to the left and right. There was a consistent trend in standing conditions of head and thorax being very close over the centre of the BoS, with the pelvis more anterior. Generally similar alignment was apparent for participants within each condition. Graphs for adults with ABI showed much greater dispersion of segments, in all directions, indicating marked postural impairments (Figure 4.6).

Table 4.1 PAD scores: Descriptive Statistics

	No. of pairs of PAD scores	Missing data: marker dropout/ missing equipment/ impaired skills	PAD mean session 1 (range)	PAD mean session 2 (range)	Paired differences between sessions *p*-value	ICC (95% CI)	MDC $_{95}$	Comparison between groups *p*-value
Healthy adults								
Sitting with rails	13	0 / 1 / 0	0.030 (0.015, 0.048)	0.027 (0.012, 0.052)	0.173†	0.876 (0.595 , 0.962)	0.008	
Sitting	14	0 / 0 / 0	0.029 (0.014, 0.055)	0.027 (0.015, 0.058)	0.594†	0.831 (0.475, 0.946)	0.012	
Standing with rails	12	1 / 1 / 0	0.089 (0.073, 0.122)	0.086 (0.072, 0.106)	0.480†	0.701 (-0.038, 0.914)	0.019	
Standing	13	1 / 0 / 0	0.085 (0.067, 0.106)	0.086 (0.063, 0.105)	0.774	0.945 (0.820, 0.983)	0.003	
Adults with ABI								
Sitting with rails	13	1 / 0 / 0	0.059 (0.019, 0.112)	0.052 (0.022, 0.111)	0.414	0.614 (-0.264, 0.882)	0.045	0.002
Sitting	11	2 / 0 / 1	0.054 (0.026, 0.099)	0.050 (0.028, 0.134)	0.328†	0.862 (0.487, 0.963)	0.020	0.001†
Standing with rails	11	0 / 0 / 3	0.105 (0.077, 0.183)	0.097 (0.077, 0.135)	0.155†	0.912 (0.674, 0.976)	0.016	0.171†
Standing	4	0 / 0 / 10	0.083 (0.072, 0.096)	0.079 (0.071, 0.087)				

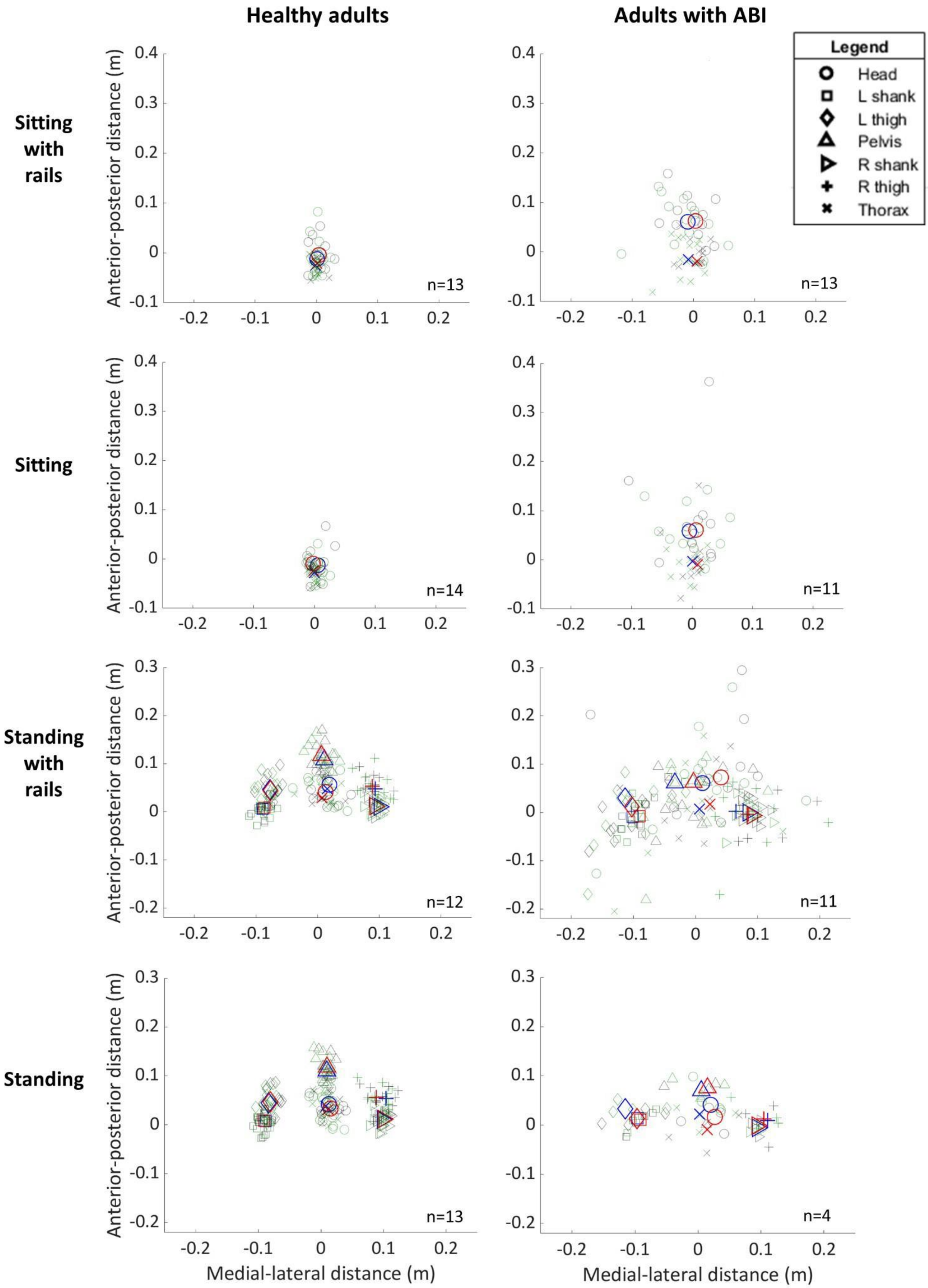
PAD: Postural Alignment and Dispersion; **Mean**: mean of PAD scores for all participants; **ICC**: Intraclass correlation coefficient (3,1);
†: non-parametric test



Centre of base of support is at 0, 0.
LTH = Left thigh; LSH = Left Shank; PEL = pelvis; RTH = Right thigh; RSH = Right shank

Figure 4.5 Examples of PAD scores and transverse plane body segment position graphs with frontal and sagittal photos

Standing with rails showed the greatest spread of body segment positions, including examples where head and thorax were posterior to the BoS, which was not seen in healthy adults. The condition with less dispersion of segments was unsupported standing; participants with the greatest alignment deficits in standing holding rails could not stand unsupported. In adults with ABI, segments in standing were generally less anterior than in healthy adults, resulting in some segments having less distance from the BoS, contributing to some lower PAD scores. PAD scores were significantly different between the two samples for sitting (p=0.002) and sitting with rails (p=0.001), but not for standing with rails (p=0.171). There were insufficient data to analyse this for standing without rails.



Centre of base of support is at 0, 0. Symbols show centre of mass of each segment.

Large Blue = Session 1 median

Large Red = Session 2 median

Small Green = all session 1 data

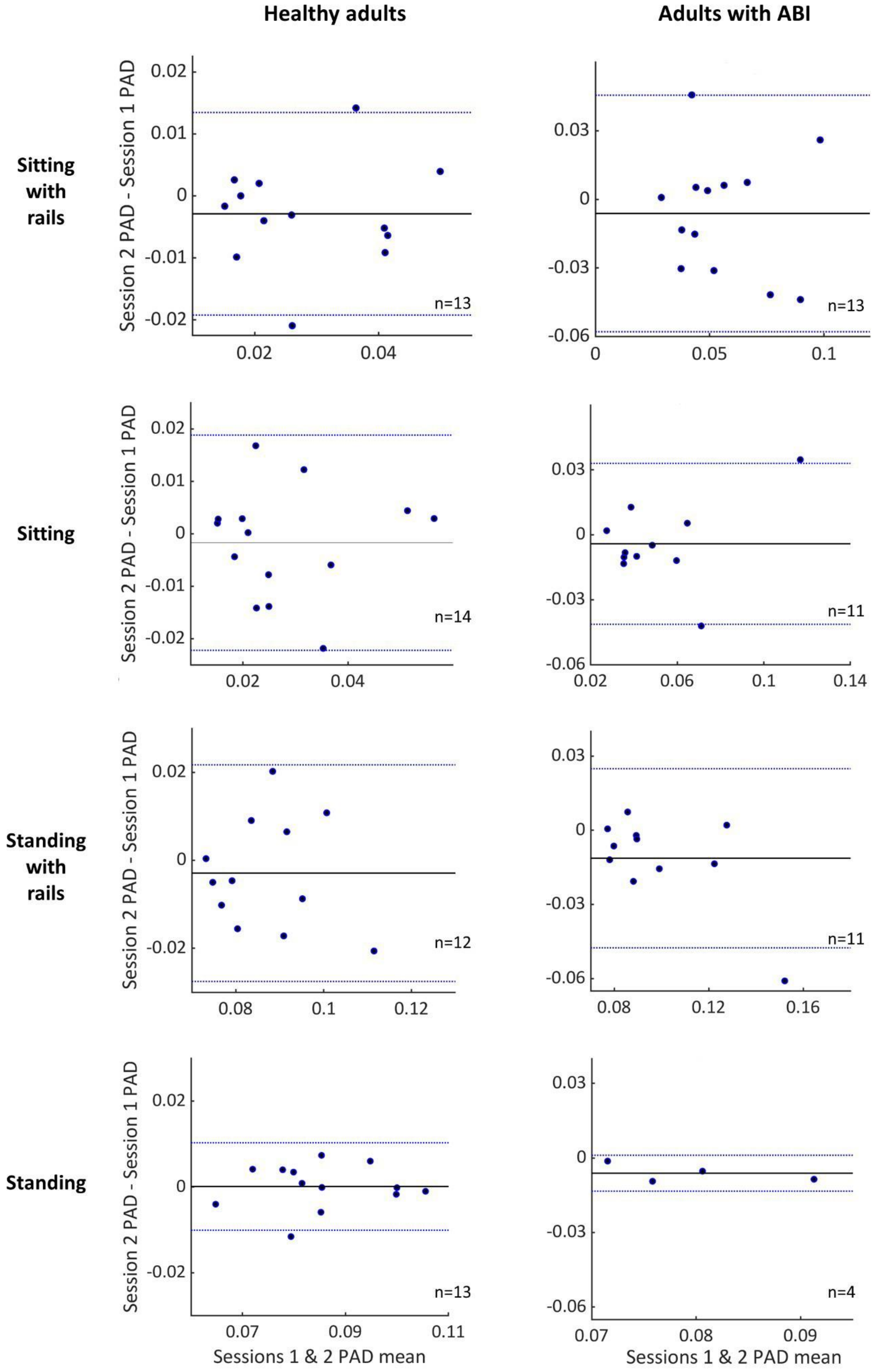
Small Black = all session 2 data

Figure 4.6 Graphs of transverse plane body segment positions

4.3.3 Repeatability

Between-sessions repeatability values are shown (Table 4.1). Healthy adults: ICC scores ranged from 0.701 (95%CI -0.038, 0.914) to 0.945 (95%CI 0.820, 0.983). ICCs were moderate for one condition, good for two conditions, and excellent for one condition. Paired samples tests showed no significant differences between session means for any condition. Bland Altman plots showed the difference between session 1 and session 2 PAD scores (y-axis) plotted against the mean of sessions 1 and 2 (x-axis) for each participant (Figure 4.7). These plots showed all differences lying within two standard deviations of the mean for two conditions; one plot showed one score lying beyond two standard deviations, the remaining plot showed two scores lying beyond two standard deviations.

Adults with ABI: ICCs of the three analysed conditions were moderate, good and excellent, ranging from 0.614 (-0.264, 0.882) to 0.912 (0.196, 0.997). There were insufficient data to calculate the ICC for unsupported standing. Paired samples tests showed no significant differences between session means. Bland Altman plots showed two conditions with all differences lying within two standard deviations, and two conditions with one score lying beyond two standard deviations (Figure 4.7).



Central line = Mean difference between sessions.
Outer lines = Two standard deviations of differences between sessions.

Figure 4.7 Bland Altman plots: Bias (difference between PAD scores in sessions 1 & 2) plotted against limits of agreement (mean of PAD scores from sessions 1 & 2)

4.4 Discussion

Greater postural deviations were observed in participants with ABI, providing new evidence of the nature of alignment changes that can occur after ABI. Participants with ABI with alignment more similar to healthy adults' on transverse plane graphs could stand unsupported (total of four out of fourteen), whereas only standing holding rails featured marked impairments of alignment. In contrast, graphs of sitting alignment showed conspicuous differences from healthy adults both with and without rails. Participants were more likely to stabilise unsupported with impaired sitting alignment than with impaired standing alignment. Ideal alignment has previously been described as "upright" when analysing spinal posture (Banno et al., 2019, Kuntz et al., 2007). A description used in this study for less variable alignment of segments, that is closer to the base of support in the transverse plane, is "compact", which is in contrast with the more dispersed body segment positions seen in adults with ABI. In all conditions, postural alignment was more compact and more consistent in healthy adults with no mobility impairment, potentially reflecting the relevance of efficient postural alignment for efficient physical function. The head and trunk tending to align almost directly over the base of support in healthy adults, in both sagittal and frontal planes, supports that this could be an indicator for correct alignment in clinical practice. The body segment mal-alignment seen in participants with ABI suggests that further research evaluating postural alignment in patients with physical impairment is warranted. While postural alignment after ABI appears to have been studied less than variables such as balance and muscle strength (Pang and Eng, 2008, Patterson et al., 2007), there are multiple variables that can potentially influence alignment. Perception of postural vertical has been shown to be significantly impaired in some people after stroke (Bergmann et al., 2016), suggesting that this could influence alignment clinically. Trunk muscles are more active in upright posture than slumped posture (O'Sullivan et al., 2002, Nairn et al., 2013), indicating that posture is relevant for understanding muscle performance. Contractures are common in adults with cerebral palsy who have postural impairment (Holmes et al., 2019). However, the scope of factors that influence postural alignment has not been established.

The PAD score provides a repeatable kinematic method for evaluating a key element of human function. Offering a single measure to reflect deviations in sagittal and frontal views provides an advantage as alignment in participants with ABI often deviated in more than one direction. Inclusion of several body segments above the base of support is relevant to clinical analysis, which requires attention to how the body aligns overall. While this study examined alignment relative to the BoS, previous studies have used other reference points for postural alignment, such as a plumbline from C7 or S1 vertebrae (Dolphens et al., 2018, McLean et al., 1996). It is apparent that these would not provide a suitable reference point for correcting alignment in some participants with ABI, due to the extent of their mal-alignment.The positive correlation between PAD scores and clinical rankings of alignment also supports that analysing alignment relative to the base of support is appropriate.

Holding rails to achieve testing positions was important to evaluate participants with severe disability. Participants with marked deficits of alignment could stand holding rails, but not achieve unsupported standing, reflecting a substantial influence of arm support. Arm support during mobility tasks has been well-documented in clinical studies (Bateni and Maki, 2005, Tyson and Rogerson, 2009), and is commonly interpreted as due to balance impairment. While differentiation of postural alignment and balance has been described in a theoretical context (Massion et al., 2004), the optimal method to do this has not yet been determined for clinical practice. Further descriptive analysis of postural alignment during function in healthy individuals will be valuable to inform analysis in clinical settings.

4.5 Study Limitations

The relatively small sample sizes limit generalisability of the results, although the low number of exclusion criteria assists with applying findings to other people with ABI and severe mobility impairment. Construct validity was evaluated in standing, chosen as the more challenging position, but was not evaluated in sitting. As validity was evaluated in people with severe mobility impairment after ABI, assessment of validity for people with less severe impairments is needed. Using photographs to evaluate validity may have meant that variations in participant performance were not reflected. Calculating PAD scores from the median values of body segment positions may have limited the scores' reflection of the most impaired alignment. Hand position on parallel bars was not standardised, as patients with physical impairment can rely on varied arm support. Rail and seat height were standardised for healthy adults, but individualised for adults with ABI. Therefore, this varied between participants, however, posture has previously been shown as not varying significantly with change in seat height in healthy adults (O'Sullivan et al., 2012). Our "whole-body" model excluded the arms, due to prioritising anti-gravity alignment of axial segments and legs. A potential limitation for analysing the PAD score is its ceiling effect. Once a participant achieves correct alignment in a task, improving their physical condition should bring no improvement in score. Analysing alignment in more advanced tasks would be required when participants have more advanced skills. Body segments did not all align exactly over each other in healthy adults, however, PAD scores do not indicate which segments have deviated from the base of support, or in which direction. The transverse plane graphs provide this additional information, so scores are best interpreted with reference to visual information about segment positions.

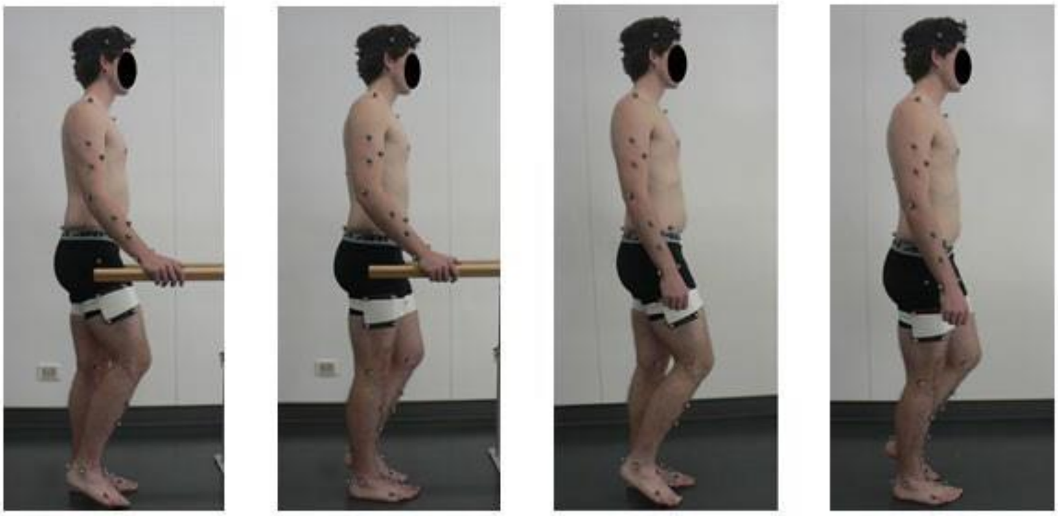
4.6 Conclusions

Whole-body postural alignment can differ between adults with and without ABI, with marked impairments seen in participants with ABI. Construct validity of PAD score measurement of postural alignment was demonstrated in adults with severe mobility impairment. Repeatability of PAD scores has been shown in clinically relevant, upright, anti-gravity positions in healthy adults and adults with ABI. Analysing postural alignment may expand opportunities to understand kinematic changes after ABI, which could assist rehabilitation practice.

Supplementary material: Postural alignment during walking

Postural alignment was also examined in walking, additional to the sitting and standing tasks described earlier. Participants who were able completed walking holding rails, walking and fast walking, and were again asked to remain “as tall and even as you can”. As eligibility required that participants with ABI were unable to walk at eight weeks post-ABI, there were insufficient numbers achieving the walking tasks to allow the statistical analyses employed for sitting and standing. The data provides some insight into exploring postural alignment during walking in people with severe mobility impairment after ABI and comparison with healthy adults.

The single-limb support phase at left and right midstance was examined, defined as the point at which the swing lateral malleolus passes the stance lateral malleolus in the sagittal plane (Figure S4.1). This aimed to examine the point of the single-leg support phase where body segments should be most upright over the stance foot. This created a left mid-stance and a right mid-stance for each walking condition. Mid-stance PAD scores were organised into more-affected side and less-affected side for adults with ABI, as assessed by a physiotherapist.



Left to right: walking with rails left mid-stance, walking with rails right mid-stance, walking left mid-stance, walking right mid-stance

Figure S4.1 Walking mid-stance testing conditions

Methods:

The experimental method matched that used for sitting and standing (see sections 4.2.2 – 4.2.4). For walking midstance, the base of support was defined as a box by the stance foot, where the longitudinal axis of the foot defined length and the inter-metatarsal distance (1st to 5th) defined width (Figure S4.2). The frames at left and right mid-stance were exported.

Graphs of transverse plane segment positions were constructed in MATLAB for each condition, for visual representation of body segment dispersion. Graphs for adults with ABI who were more affected on their right side were reversed so all more-affected midstance appear on the left, and all less-affected midstance on the right.

For healthy adults, inter-session repeatability of PAD scores was calculated with intraclass correlation coefficients ($ICC_{3,1}$). Paired t-tests assessed for differences between session means. Results were considered significant with $p \leq 0.05$.

For healthy adults, Bland Altman plots were constructed to check for a proportional bias of scores above or below the mean difference between sessions, for each condition.

Results:

Descriptive PAD score data are shown in Table S4.1. PAD scores were higher in healthy adults, which appears to be due to the relatively posterior positions of body segments in adults with ABI, with less average segment distance from the BoS than healthy adults (shown in Figures S4.3 – S4.4).

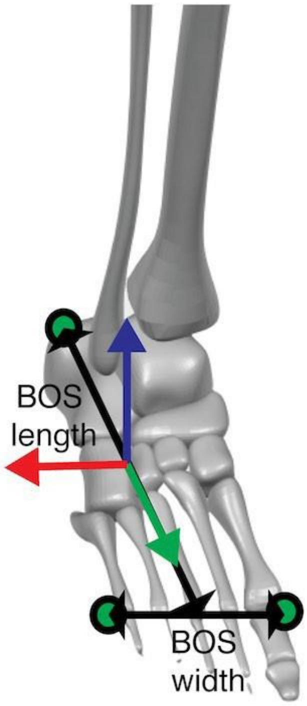


Figure S4.2 Walking base of support coordinate system

Transverse plane segment position graphs:

Centre of mass positions for each body segment were graphed relative to the base of support (Figures S4.3 and S4.4).

Healthy adults: generally similar alignment was apparent for participants within each condition. Stance phase segments (head, thorax, pelvis, thigh, shank) were clustered around the BoS in left and right mid-stance. There were no body segments in any condition positioned posterior to the centre of the BoS. There was greater variation in distribution of segments in fast walking, including more anterior position of the head in some participants, and greater variation in swing phase segments (swing thigh and shank). It was apparent that the method used to define mid-stance resulted in healthy adults' upper body segments being slightly in front of the BoS, rather than directly over it.

Adults with ABI: much more variation in dispersion of segments was apparent. Disordered spread of segments was apparent in both more-affected and less-affected mid-stance. In walking with rails, some segments were posterior to the BoS. In participants who could walk unsupported, segments posterior to the BoS were seen only in weaker mid-stance. The relatively posterior position of body segments appeared to be why adults with ABI had lower PAD scores than healthy adults, with less average segment distance from the BoS.

Repeatability:

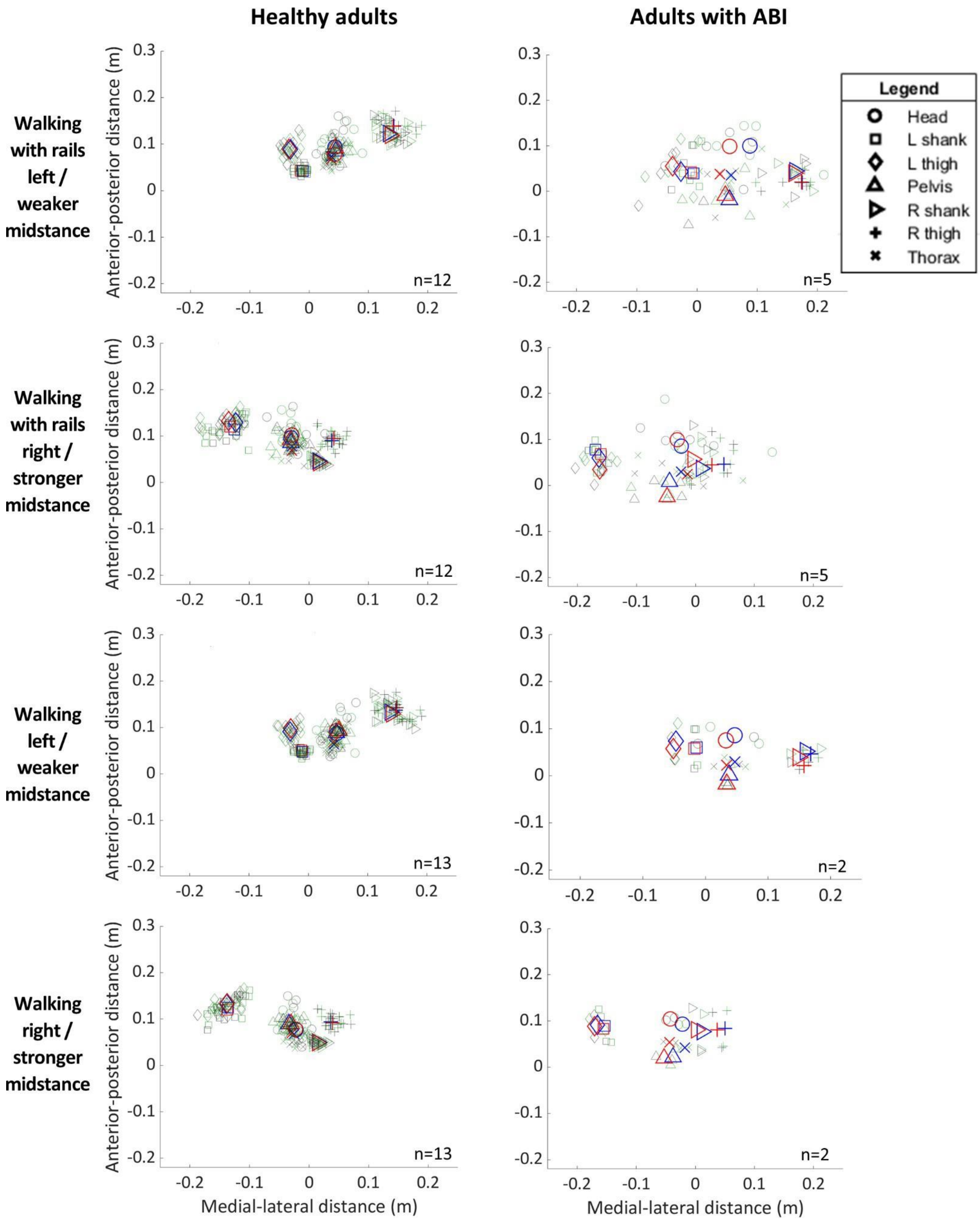
Healthy adults: ICCs were moderate for one mid-stance condition and good for five mid-stance conditions. Paired t-tests showed no significant differences between session means for any condition (Table S4.1).

Adults with ABI: There were insufficient data to analyse repeatability of PAD scores.

Summary:

Results provide an insight into postural alignment during walking mid-stance in healthy adults. Differences in alignment at mid-stance were apparent in the participants with ABI who could walk. Further study of postural alignment during walking is required to understand changes after ABI and how these can best be measured.

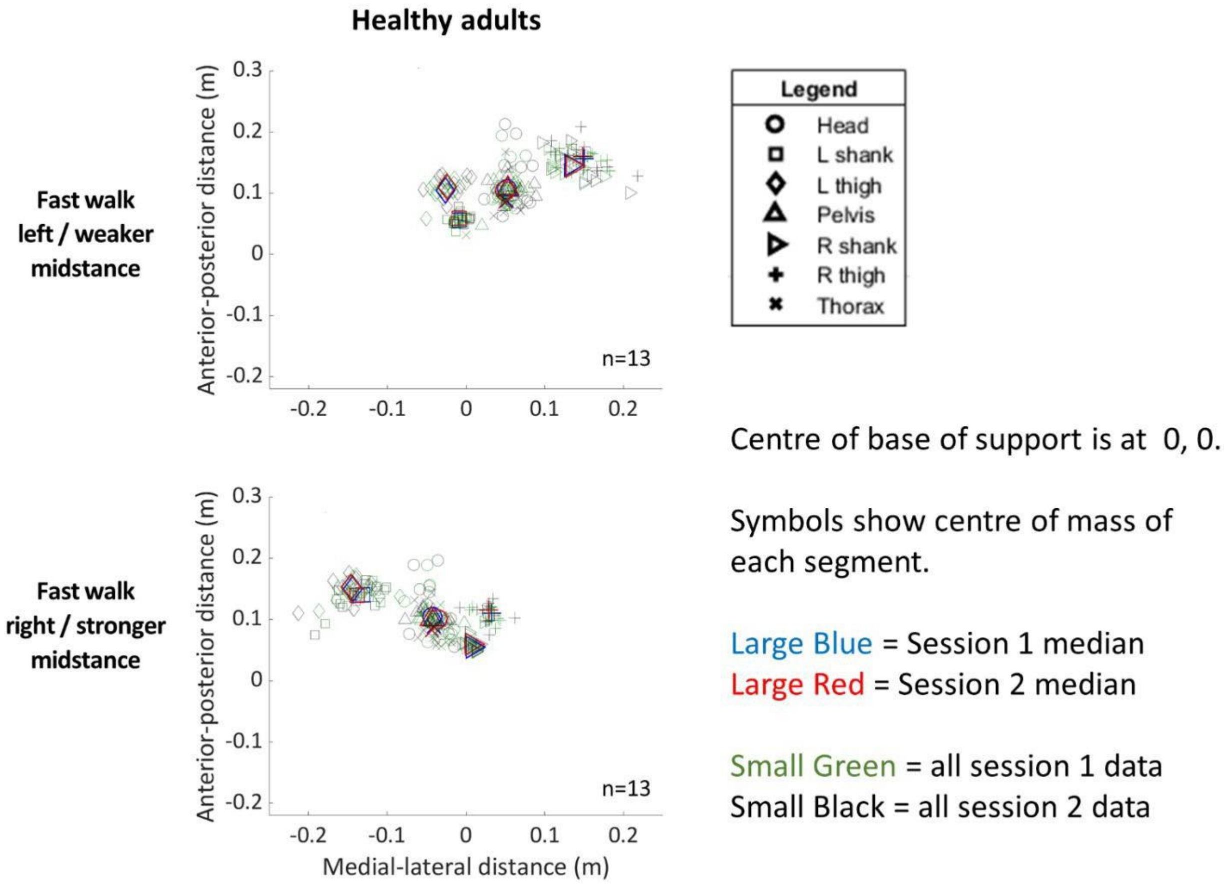
Videos of walking mid-stance with transverse plane segment position graphs and PAD scores are available at https://vimeo.com/452237143.



Symbols show centre of mass of each segment. Centre of base of support is at 0, 0. Adults with ABI who are weaker on the right have their segment positions reversed so all weaker mid-stance are displayed on the left

Large Blue = Session 1 median
Large Red = Session 2 median
Small Green = all session 1 data
Small Black = all session 2 data

Figure S4.3 Transverse plane graphs of body segment positions



Centre of base of support is at 0, 0.

Symbols show centre of mass of each segment.

Large Blue = Session 1 median
Large Red = Session 2 median

Small Green = all session 1 data
Small Black = all session 2 data

Figure S4.4 Transverse plane graphs of body segment positions (fast walk)

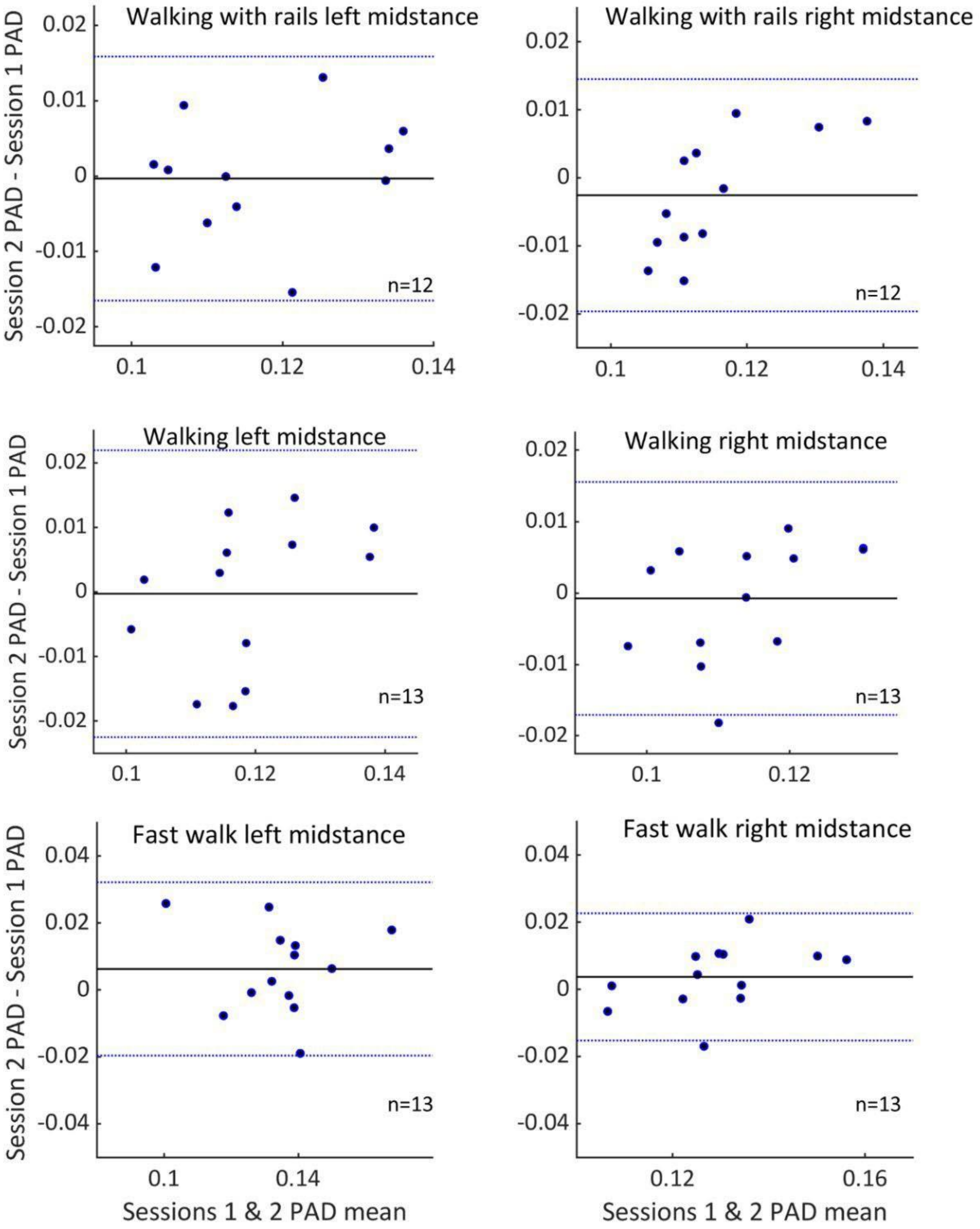
Table S4.1 Walking conditions PAD scores: Descriptive Statistics

	No. of pairs of PAD scores	Missing data: marker dropout/ missing equipment/ impaired skills	PAD mean session 1 (range)	PAD mean session 2 (range)	Paired differences test *p*-value	ICC (95% CI)	MDC $_{95}$
Healthy adults							
Walk with rails left midstance	12	1 / 1 / 0	0.117 (0.102, 0.134)	0.117 (0.097, 0.139)	0.888	0.892 (0.624, 0.969)	0.008
Walk with rails right midstance	12	1 / 1 / 0	0.116 (0.109, 0.133)	0.114 (0.099, 0.142)	0.331	0.798 (0.297, 0.942)	0.011
Walk left midstance	13	1 / 0 / 0	0.119 (0.102, 0.135)	0.118 (0.098, 0.143)	0.931	0.747 (0.169, 0.923)	0.017
Walk right midstance	13	1 / 0 / 0	0.114 (0.099, 0.127)	0.113 (0.094, 0.133)	0.750	0.835 (0.460, 0.950)	0.009
Fast walk left midstance	13	1 / 0 / 0	0.132 (0.088, 0.159)	0.138 (0.114, 0.177)	0.114	0.824 (0.423, 0.946)	0.015
Fast walk right midstance	13	1 / 0 / 0	0.128 (0.107, 0.152)	0.131 (0.103, 0.161)	0.193	0.881 (0.609, 0.964)	0.009
Adults with ABI							
Walk with rails more-affected midstance	5	0 / 0 / 9	0.106 (0.089, 0.125)	0.093 (0.083, 0.107)			
Walk with rails less-affected midstance	5	0 / 0 / 9	0.101 (0.093, 0.121)	0.097 (0.082, 0.116)			
Walk more-affected midstance	2	0 / 0 / 12	0.097 (0.097, 0.097)	0.085 (0.080, 0.089)			
Walk less-affected midstance	2	0 / 0 / 12	0.102 (0.101, 0.103)	0.108 (0.102, 0.113)			
Fast walk more-affected midstance	1	0 / 0 / 13	0.122	0.103			
Fast walk less-affected midstance	1	0 / 0 / 13	0.131	0.107			

PAD: Postural Alignment and Dispersion; **Mean**: mean of PAD scores for all participants; **ICC**: Intraclass correlation coefficient (3,1); **MDC$_{95}$**: Minimum detectable change, calculated at 95% confidence interval; **95% CI**: 95% confidence interval

Bland Altman plots:

Plots for healthy adults showed all differences lying within two standard deviations of the mean for four conditions; two plots showed one score lying beyond two standard deviations (Figure S4.5). There were insufficient data to construct plots for adults with ABI.



Central line = Mean difference between sessions.
Outer lines = Two standard deviations of differences between sessions.

Figure S4.5 Bland Altman plots for healthy adults: Bias (difference between PAD scores in sessions 1 & 2) plotted against limits of agreement (mean of PAD scores from sessions 1 & 2)

Chapter 5

Improvement in postural alignment in sitting and standing is associated with recovery of mobility after acquired brain injury: an observational study

This manuscript has been prepared for submission to the Journal of Physiotherapy:

Mills SJ, Mackintosh S, McDonnell MN, Thewlis D: Improvement in postural alignment in sitting and standing is associated with recovery of mobility after acquired brain injury: an observational study

Abstract

Questions: (1) How does mobility change over six months in people unable to walk at eight weeks post-Acquired Brain Injury (ABI)? (2) Is there an association over time between postural alignment and mobility post-ABI? (3) Does postural alignment after ABI become closer to healthy alignment over time?

Design: Prospective, longitudinal, observational study.

Participants: Fourteen adults with ABI admitted to inpatient rehabilitation, evaluated at baseline, three months and six months, and a reference sample of 30 healthy adults.

Outcome measures: Changes in mobility were assessed using the Clinical Outcome Variables Scale (COVS), sit-to-stand, timed standing holding rails, independent walking speed and number of testing conditions achieved. The Functional Independence Measure (FIM) was scored at admission and discharge. To measure postural alignment, participants were recorded in sitting and standing, each repeated holding rails. Three-dimensional kinematic data were used to quantify whole-body postural alignment, equal to average segment displacements from the base of support in the transverse plane. Associations between alignment scores and COVS scores were calculated using Linear Mixed-Effects Models.

Results: Participants made significant improvements in COVS scores, most secondary mobility scores, and FIM scores over time (p=<0.001). Relationships between increasing COVS scores and decreasing mal-alignment scores were statistically significant for all sitting and standing conditions. Visual analysis of graphed segment positions indicated that sitting and standing alignment became more compact over time; this was not clear for walking mid-stance.

Conclusion: Improvement in postural alignment may be a factor for improving mobility after ABI.

5.1 Introduction

Acquired brain injury (ABI) can have a devastating impact on the lives of survivors (Hawthorne et al., 2009). Mobility impairment occurs frequently, and recovering mobility is often the highest priority for survivors, but recovery can be limited (Carlozzi et al., 2011, Tate et al., 2012). Further, studies report that people who fail to recover independence with basic mobility within the first two months after ABI are unlikely to achieve this (Katz et al., 2004, Jorgensen et al., 1995). However, evidence shows that people who are slow-to-recover, or have severe deficits, can make progress beyond this timeframe (Hammond et al., 2019, Preston et al., 2011, Hayward et al., 2014). Despite this, more severe disability has sometimes resulted in patients being excluded from rehabilitation (Lynch et al., 2019, Nguyen et al., 2007, Santos et al., 2011).

Many studies have investigated recovery of independent walking, however, there is less research exploring other aspects of mobility after ABI (Craig et al., 2011), such as assisted mobility, which may be important for those with severe impairments. Kinematic variables can change after ABI (Boudarham et al., 2013, Conte et al., 2014), but the critical variables for clinical attention are not clear for assisted mobility. Healthy walking is most frequently measured by velocity, cadence or step/stride length, rather than data from the upper body (Roberts et al., 2017). However, clinically, it is common to see changes involving the upper body after ABI, including altered postural alignment. This may have significant implications, as upright postural alignment is usual in healthy standing and walking (Ferreira et al., 2011, Cromwell et al., 2001). Marked impairments of postural alignment can be observed after ABI, affecting whole-body alignment (Karnath, 2007). Despite this, alignment of body segments has received little attention in biomechanical research after ABI (Mills et al., 2017).

We recently developed a new approach for quantifying postural alignment relative to the base of support (BoS), the Postural Alignment and Dispersion (PAD) score, which was evaluated in sitting and standing. Anecdotally, impaired whole-body postural alignment becoming more upright seems important for progressing mobility, particularly for those with severe impairments after ABI, but this has not previously been investigated (Mills et al., 2017). This study sought to investigate this observation, in adults not walking at eight weeks post-ABI, when literature suggests that prognosis is limited (Katz et al., 2004, Jorgensen et al., 1995). The study also sought to determine if body segment distributions appeared to become closer to healthy adults' segment distributions over time. The research questions were:

1. How does mobility progress in people not walking at eight weeks post-ABI?
2. What is the association over time between mobility and postural alignment in sitting and standing?
3. Does postural alignment in sitting, standing and walking become closer to healthy alignment over time?

5.2 Methods

5.2.1 Design

An observational study with prospective, longitudinal data collected in adults with ABI, at baseline, three months and six months, and comparison data from healthy adults.

5.2.2 Participants

Adults with ABI: potential participants were screened from consecutive admissions to inpatient ABI rehabilitation between December 2015 and July 2017, who were not walking at eight weeks post-ABI (scoring <3/7 on items eight and nine of the Clinical Outcome Variables Scale (COVS)). They were excluded if their mobility impairment was not due to their recent ABI, they had a degenerative neurological condition, or bony landmarks unable to be located (typically with Body Mass Index > 35 kg/m^2). The eligibility criteria were evaluated throughout inpatient rehabilitation and eligilbity could occur later than eight weeks post-ABI; for entry participants needed to manage at least one testing condition, for at least five seconds. Participants who were ineligible due to orthopaedic restrictions were reviewed for eligibility once the orthopaedic status was revised.

Healthy Adults: a convenience sample was recruited (see section 4.2.1)

5.2.3 Procedure

Kinematic data were collected in seven tasks relevant to function and rehabilitation: sitting, standing, walking at self-selected speed, and fast walking, with the first three conditions repeated with parallel bars, to allow inclusion of those reliant on support. Participants completed the tasks that they could. Sixty-nine retroreflective markers (14 mm diameter) were positioned on anatomical landmarks (see section 4.2.2). Participants were instructed to stay "as tall and even as you can". Three 30 second trials were recorded for sitting and standing tasks. If not clear whether a participant could manage a condition, clinical judgement was used, gauged by their willingness to try and graded withdrawal of assistance. Available data were included if a participant could not manage all three trials or the full 30 seconds. Still and video recordings were used for checking of marker labelling during 3D model construction. This protocol was undertaken by participants with ABI at baseline, then three months and six months following baseline, and once by healthy adults. Data from 14 of the healthy adults were also reported in Chapter 4. Mobility measures were also completed by adults with ABI at each time point.

For adults with ABI, kinematic data were collected using a 12 camera Optitrack motion capture system and AMASS software (C-Motion, Inc., USA), which has been shown to be comparably accurate to the industry reference standard (Thewlis et al., 2013). For healthy adults, kinematic data were collected using a 12 camera Vicon MX-F20 motion capture system (Vicon Motion Systems, Oxford Metrics, Oxford, UK). All data were exported to Visual3D (Version 6, C-Motion, Inc., USA) in .c3d format for post-processing. Postural alignment was determined using a definition of alignment of body segments relative to each other when upright (Fortin et al., 2011). From the marker trajectories, body segments (head, thorax, pelvis, thighs, lower legs, feet) were defined by anatomical coordinate systems (Cappozzo et al., 1995), and modelled with six degrees of freedom. The arms were excluded, to prioritise axial and leg segments' alignment. For each task, a BoS coordinate system was established. The centre of mass (COM) coordinates for all body segments above the BoS (sitting: head and thorax; walking mid-stance and standing: every segment excluding the feet) were exported to MATLAB (The Mathworks, USA) for processing using custom-written code. For sitting and standing, the median segment COM positions were exported. Walking data were exported at left and right mid-stance, defined as the point of the swing lateral malleolus passing the stance lateral malleolus in the sagittal plane. Left and right mid-stance for adults with ABI for each walking condition were relabelled as more-affected or less-affected, as assessed by an experienced physiotherapist.

5.2.4 Outcome measures

Mobility was measured using the COVS, a valid and reliable measure after ABI, of 13 items scored 1-7 (Seaby and Torrance, 1989, Low Choy et al., 2002, Salter et al., 2010). Lower scores indicate greater impairment; the minimal clinically important difference has been reported as five points (Barclay-Goddard, 2000). Secondary mobility measures were: sit-to-stand scored 0-7 (Perry et al., 2006); timed standing holding rails (timed with a stopwatch during kinematic recording, up to 30 seconds, to establish if a standing position could be maintained; participants who could not achieve this condition scored zero); self-selected independent walking speed (calculated from kinematic recording using Visual3D software; those who did not walk independently scored zero); and number of test conditions achieved (sum (1-7) of how many postural tests participants could perform, used to evaluate if achieving more upright tasks was associated with mobility improvements). FIM motor and total scores were determined by accredited staff at rehabilitation admission and discharge. PAD scores measured postural alignment in sitting and standing. Calculating PAD scores is described in detail in Chapter 4; in brief, the segments' COM coordinates in the transverse plane were expressed relative to the BoS coordinate system. For body segments above the BoS, the PAD score represents the sum of these segments' transverse plane distances from the centre of the BoS, divided by the number of segments. This enabled deviations in both frontal and sagittal planes to be represented.

5.2.5 Data analysis

Normality of distributions was assessed using Shapiro-Wilk tests and histograms. Linear Mixed-Effects Models were used to analyse change in mobility measures over time, and associations between COVS scores and each PAD score over time. Estimates of Fixed Effects indicated the estimated change in COVS score that would accompany a change in PAD score. Assumptions of a linear model were evaluated by inspection of histograms and scatterplots of residuals and predicted values. As the psychometric properties of PAD scores for walking have not previously been evaluated, walking PAD scores were not included in statistical analysis. Wilcoxon Signed Rank Tests evaluated change in FIM scores between rehabilitation admission and discharge. Results were considered statistically significant with $p \leq 0.05$. Graphs of transverse plane body segment positions were constructed for all participants in each condition, for visual analysis of postural alignment.

5.3 Results

5.3.1 Participants

From 252 consecutive admissions to ABI rehabilitation screened, 32 met the mobility impairment inclusion criterion. Of these, exclusions were due to: inability to achieve any testing condition or follow instructions adequately (n=8); inability to participate due to medical issues, fatigue or nausea (n=5); or bony landmarks unable to be located (n=3). One eligible adult declined to take part. Fifteen adults with ABI entered the study; one was unable to adequately follow instructions at the first session and was withdrawn. Therefore, fourteen participants were included (seven men, seven women), with descriptive data shown (Table 5.1). Mean age at baseline was 43 years (range 20-75 years), mean height 1.70 m (range 1.55-1.82 m), mean mass 68 kg (range 50-105 kg). One participant missed postural data collection at six months, there was no other loss to follow-up. 30 healthy adults (20 men, 10 women) were recruited. Mean age was 36 years (range 18-76 years), mean height 1.72 m (range 1.53-1.87 m), mean mass 72 kg (range 47-111 kg).

5.3.2 Functional outcomes

Data are presented (Tables 5.1 and 5.2). Participants made statistically significant improvements in most mobility measures (COVS, sit-to-stand, independent walking speed, number of conditions achieved) and FIM motor and total scores (p=<0.001). Assumptions of a linear model were not upheld for timed standing with rails, consequently a binary logistic Generalized Estimating Equation (GEE) model was used, which indicated that improvement in standing with rails times was not statistically significant (p=0.099) (Figure 5.1).

5.3.3 Associations between postural alignment and mobility over time

PAD score descriptive data are shown (Table 5.3). There was a statistically significant association between COVS and sitting with rails PAD scores, adjusting for time (p=<0.001). For every 0.05 decrease in sitting with rails PAD (segments more aligned over the BoS), the mean COVS increased by 10.2 (95%CI 5.4, 15.0). Significant associations were also seen for sitting, standing with rails and standing ($p < 0.05$). Assumptions of a linear model were found to be upheld, results are presented (Table 5.4).

Table 5.1 Adults with ABI: participant data

	Age group	ABI classification	Lowest GCS recorded in first 24 hours	Days injury to rehab admission	Days injury to baseline	Rehab length of stay (days)	Baseline BMI	Admission FIM motor / total	Discharge FIM motor / total	Baseline COVS score	6 Month COVS score
P01	70 – 79	Stroke	14	38	123	113	35.1	16 / 41	44 / 70	44	48
P02	20 – 29	TBI	4	54	107	141	17.9	13 / 21	48 / 64	42	59
P03	60 – 69	Hypoxic	4	51	85	112	19.9	13 / 18	47 / 66	40	80
P04	50 – 59	SAH	12	27	55	161	24.4	13 / 27	45 / 65	25	64
P05	70 – 79	SAH	4	72	101	38	28.8	16 / 25	72 / 96	75	90
P06	40 – 49	SAH	13	46	66	72	18.3	23 / 48	70 / 98	38	72
P07	40 – 49	TBI	8	33	69	107	23.6	21 /28	39 / 62	31	49
P08	60 – 69	Hypoxic	†	62	78	42	27.3	45 / 66	80 / 106	78	89
P09	40 – 49	SAH	10	59	114	142	24.1	14 / 24	69 / 95	37	59
P10	20 – 29	TBI	4	40	61	99	19.4	13 / 18	78 / 107	43	85
P11	20 – 29	Hypoxic	3	91	290	134	18.5	13 / 18	13 / 24	20	19
P12	20 – 29	SAH	4	88	157	158	21.1	13 / 18	51 / 69	26	77
P13	30 – 39	TBI	5	42	81	89	27.2	13 / 20	70 / 93	48	82
P14	20 – 29	TBI	†	19	58	145	21.7	13 / 22	75 / 105	48	70
		Mean (SD)	7 (4)	52 (21)	103 (61)	111 (40)	23 (5)	17 (9) / 28 (14)	57 (19) / 80 (24)	43 (17)	67 (20)

ABI: Acquired Brain Injury; **GCS**: Glasgow Coma Scale; **BMI**: Body Mass Index; **FIM**: Functional Independence Measure; **COVS**: Clinical Outcome Variables Scale; **TBI**: Traumatic Brain Injury; **SAH**: Subarachnoid haemorrhage; †Data not available

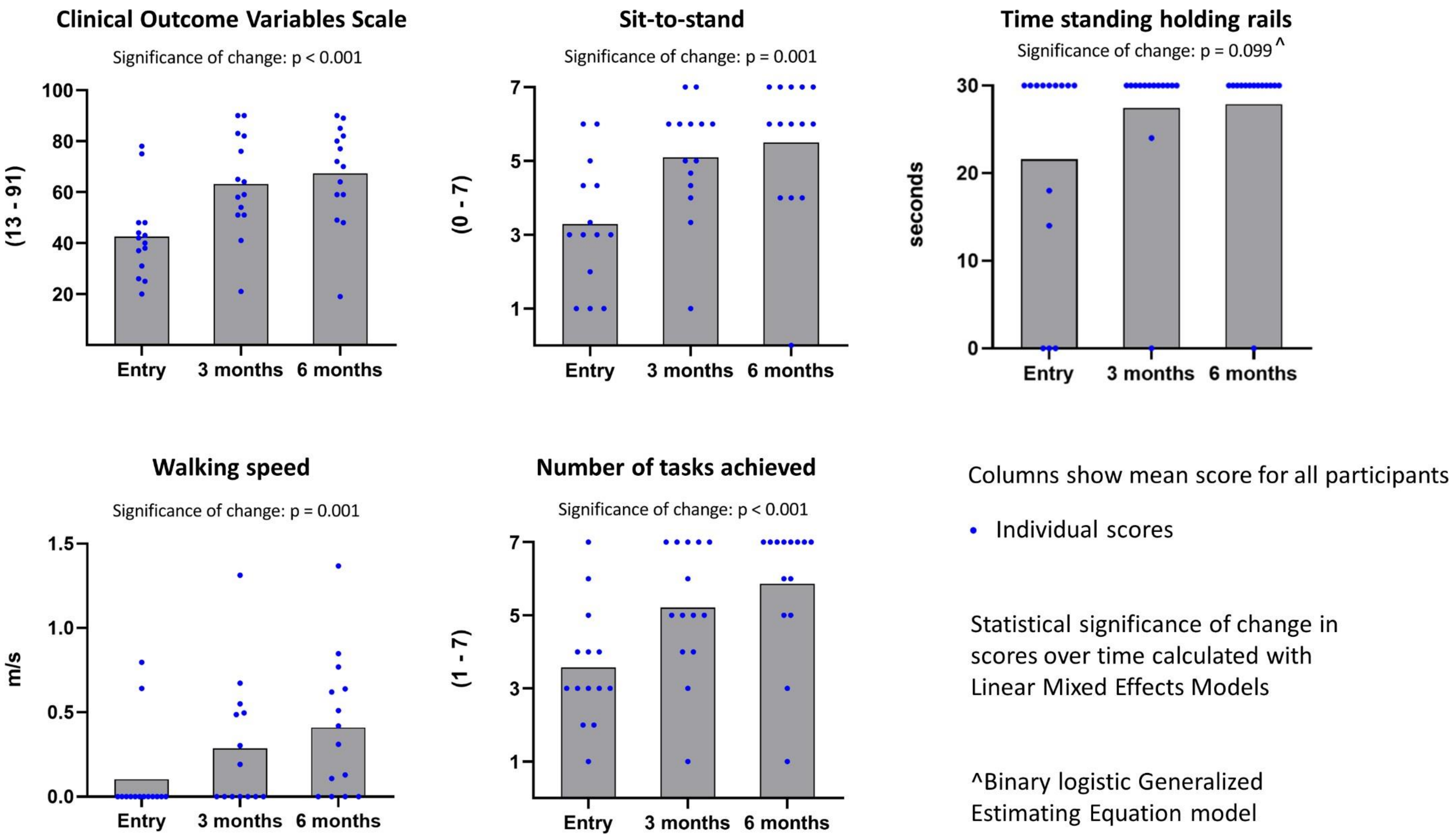
Table 5.2 Mobility scores over time: Linear Mixed-Effects Models

	Baseline mean (SD)	Baseline range	3 months mean (SD)	3 months range	6 months mean (SD)	6 months range	***p*-value**
Clinical Outcome Variables Scale (13 – 91)	42.5 (16.8)	20 – 78	63.2 (19.7)	21 – 90	67.4 (19.6)	19 - 90	<0.001
Sit to stand (0 – 7)	3.3 (1.7)	1 - 6	5.1 (1.6)	1 – 7	5.5 (2.0)	0 - 7	0.001
Timed standing with rails (0 – 30)	21.6 (12.7)	0 – 30	27.4 (8.1)	0 – 30	27.9 (8.0)	0 - 30	0.099^
Walk speed (m/sec)	0.10 (0.26)	0 – 0.80	0.29 (0.39)	0 – 1.31	0.37 (0.42)	0 - 1.37	0.001
No. of conditions achieved (1 – 7)	3.6 (1.6)	1 - 7	5.2 (1.8)	1 – 7	5.9 (1.8)	1 - 7	<0.001

^Binary logistic Generalized Estimating Equation model (modelling the probability that time standing with rails=30sec)

Table 5.3 Postural Alignment and Dispersion (PAD) scores over time

	PAD mean Baseline (range)	PAD mean 3 months (range)	PAD mean 6 months (range)	Baseline n =	3 months n =	6 months n =	Scores missing due to participant's skill level / marker dropout	Participant absent at 6 months
Sitting with Rails	0.058 (0.019, 0.112)	0.055 (0.015, 0.226)	0.051 (0.013, 0.240)	13	13	12	0 / 3	1
Sitting	0.054 (0.026, 0.099)	0.042 (0.018, 0.094)	0.037 (0.019, 0.063)	11	11	9	3 / 7	1
Standing with Rails	0.105 (0.077, 0.183)	0.095 (0.073, 0.125)	0.092 (0.081, 0.117)	11	12	12	5/ 1	1
Standing	0.083 (0.072, 0.096)	0.088 (0.075, 0.109)	0.092 (0.077, 0.107)	4	9	11	16 / 1	1


Clinical Outcome Variables Scale

Significance of change: p < 0.001

Sit-to-stand

Significance of change: p = 0.001

Time standing holding rails

Significance of change: p = 0.099 ^

Walking speed

Significance of change: p = 0.001

Number of tasks achieved

Significance of change: p < 0.001

Columns show mean score for all participants

- Individual scores

Statistical significance of change in scores over time calculated with Linear Mixed Effects Models

^Binary logistic Generalized Estimating Equation model

Figure 5.1 Change in functional scores over six months

Table 5.4 Associations between mobility (COVS) and alignment (PAD) scores over time: Linear Mixed-Effects Models

	p-value	Estimate of COVS change with 0.05 decrease in PAD (95% CI)
Sitting with rails	<0.001	10.2 (5.4, 15.0)
Sitting	0.011	12.5 (3.2, 21.7)
Standing with rails	0.039	8.3 (0.5, 16.2)
Standing	0.020	24.1 (4.3, 43.8)

95% CI: 95% confidence intervals of estimates of COVS change

5.3.4 Transverse plane body segment positions

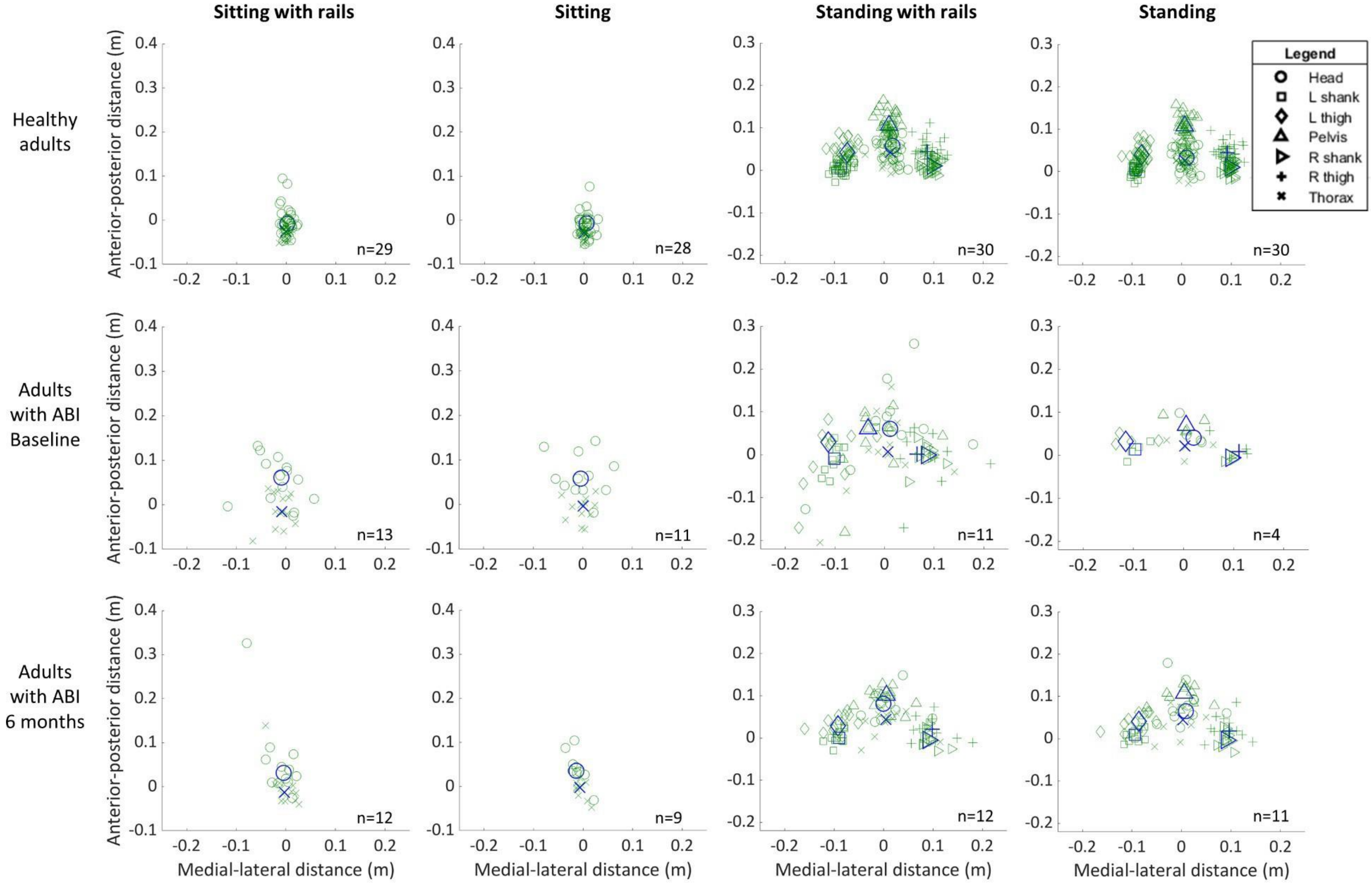
Graphs showed more consistent alignment for healthy adults in each condition. After ABI, there was greater dispersion of body segments in sitting and standing at baseline, with alignment more compact (similar to healthy adults) at six months (Figure 5.2). Examples comparing graphs with PAD scores and photos are shown (Figure 5.3). Walking mid-stance segment dispersions differed between samples at both timepoints; alignment did not appear to normalise as much over time as in sitting/standing (Figure 5.4). Alignment appeared to be impaired in less-affected mid-stance as well as more-affected mid-stance, particularly for walking with rails. The only extreme segment positions at six months were in conditions holding rails, suggesting that participants with persistent, severe mal-alignment were less likely to achieve unsupported tasks. Supplementary material comparing graphs with walking videos is available at https://vimeo.com/452243182.

5.3.5 Relationship between Glasgow Coma Scale and outcome

Post-hoc analysis showed a wide variation in lowest Glasgow Coma Scale (GCS) scores in the first 24 hours post-ABI (range 3-14). Spearman correlation coefficients were calculated for Glasgow Coma Scale scores with initial and final FIM and COVS scores. Correlation was statistically significant for entry FIM score (ρ=0.838, p=0.001) and not significant for discharge FIM score or COVS scores (p=0.412-0.813) (Table 5.5).

Table 5.5 Correlations between Glasgow Coma Scale and outcome scores

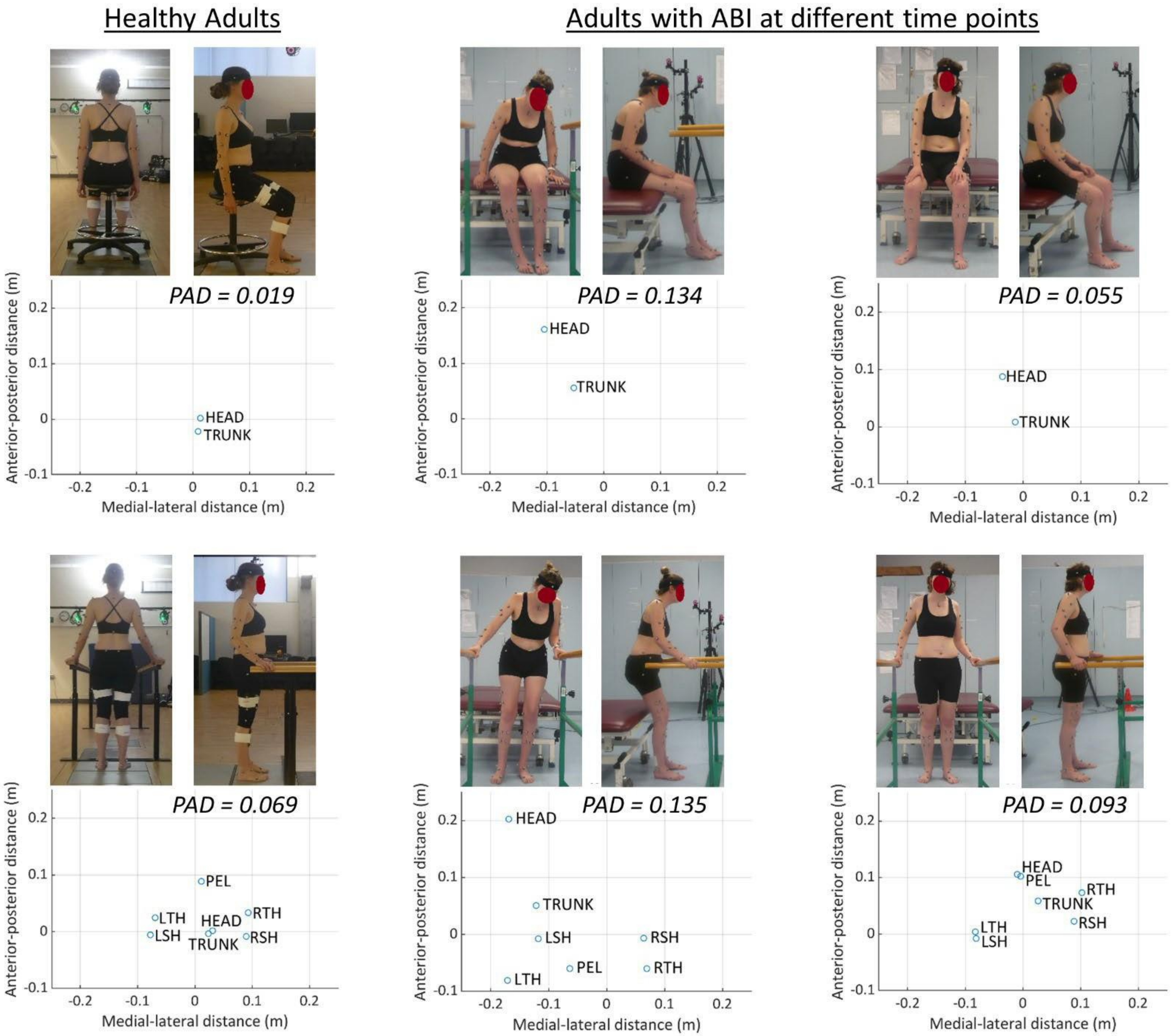
	Correlation coefficient (ρ)	*p*-value
Entry FIM	.838	.001
Discharge FIM	.261	.412
Baseline COVS	.073	.823
6 month COVS	-.236	.460



Centre of base of support is at 0, 0. Symbols show centre of mass of each segment.

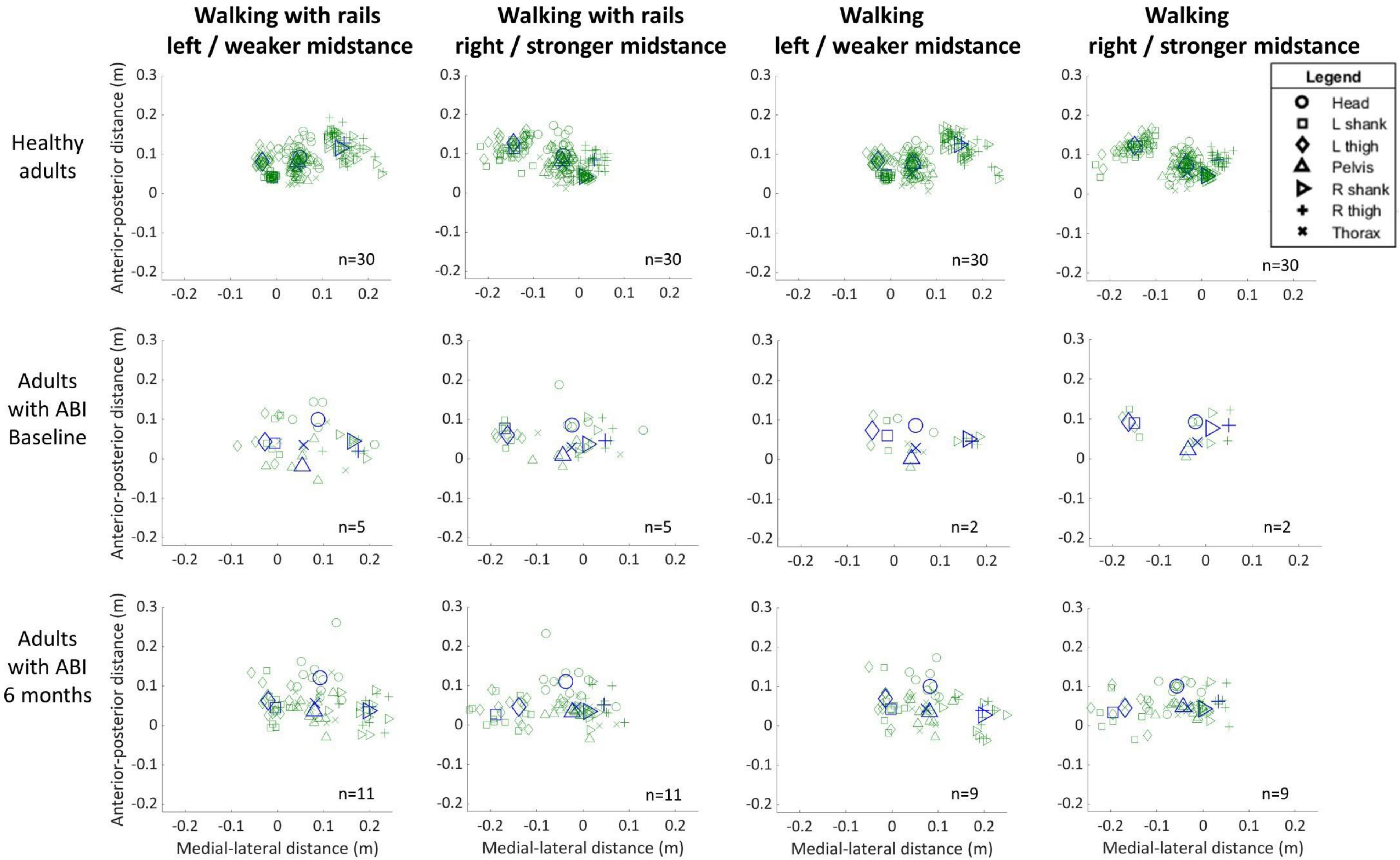
Large symbols = median scores Small symbols = all individual scores

Figure 5.2 Transverse plane body segment positions over time, compared with healthy adults: sitting and standing conditions



Graphs: centre of base of support is at 0, 0. Symbols show centre of mass position for each segment.
LTH = Left thigh; LSH = Left shank; PEL = Pelvis; RTH = Right thigh; RSH = Right shank

Figure 5.3 Examples of PAD scores and transverse plane segment position graphs with frontal and sagittal photos



Centre of base of support is at 0, 0. Symbols show centre of mass of each segment. Adults with ABI with weaker side on right have segments reversed so all weaker mid-stance show on left. Large symbols = median scores Small symbols = all individual scores

Figure 5.4 Transverse plane body segment positions over time, compared with healthy adults: walking conditions

5.4 Discussion

This study provides new evidence of an association between improvement in whole-body postural alignment and progress with mobility skills. Body segments aligning more directly over the base of support in sitting and standing, with and without rails, was associated with improved mobility scores. This supports the clinical hypothesis that improving alignment relative to the base of support can accompany recovery of mobility after ABI. Mean PAD scores decreased over time for sitting, sitting with rails and standing with rails, whereas mean PAD score increased for standing. Some participants could not stand unsupported at baseline; participants recovering unsupported standing later caused higher mean standing PAD scores at three and six months. Higher mean PAD scores are evident in the conditions with rails, for both sitting and standing. This is due to conditions with rails having the most extreme PAD scores (highest values). There were more participants in the conditions with rails, suggesting that the most mal-aligned participants did not achieve the unsupported conditions.

The results suggest that analysing whole-body postural alignment, at least in sitting and standing, is important for understanding progress with mobility in ABI rehabilitation. This provides a basis for considering updates to clinical practice. The variations in segment positions suggest that a whole-body approach to analysing alignment is needed, and indicates that both sagittal and frontal plane analysis is required. Walking mid-stance represents anti- gravity alignment in the single leg support phase and aimed to examine the point where body segments should be most upright over the stance foot. While it could be seen that mid-stance body segment distribution was still different to healthy adults after six months, measurement of alignment during walking requires future investigation.

Further analysis of postural alignment changes in people with functional impairment is needed to inform key indicators for clinical assessment. For example, participants with ABI had much greater asymmetry of standing alignment in the frontal plane than healthy adults and also had upper body segments aligning posterior to the base of support in standing. Defining the range of key features of altered alignment that highlight the need for further clinical attention would assist clinical practice.

Methods of analysing posture vary in previous research, for example some studies measuring centre of pressure rather than alignment of body segments (Paillex and So, 2005, Perlmutter et al., 2010), suggesting that terminology and concepts of stability and alignment may not be consistently differentiated in the literature. Alignment in standing has been measured using individual segment angles relative to upright (Krawczky et al., 2014, Fortin et al., 2011). While the present study has used kinematic data to produce a whole-body measure, a clinical scale to do this quickly remains lacking. Trunk performance has several scales available (Sorrentino et al., 2018), however, included items are primarily in sitting or lying, and none score upright posture. Posture is a key role of trunk muscles, including in standing and walking (Preuss and Fung, 2008, van Dieen et al., 2018, Cromwell et al., 2001), so alignment may give useful information about trunk performance.

Published examples of impaired postural alignment have described the effect of altered perception of vertical after stroke, resulting in “pushing behaviour” (Karnath, 2007). Our study has not examined whether impaired midline perception was present, nor other potential factors, such as weakness, contractures or pain. Future studies are needed to identify the factors that affect postural alignment, and the optimal methods to differentiate them. A balance measure was not recorded, but the fact that support from rails did not allow all participants to stand and walk suggests that balance impairment was not the primary barrier. Assisting mobility in the presence of pushing behaviour has been described as difficult (Karnath, 2007), but the impact of patients’ alignment on carers’ manual handling has yet to be investigated.

The significant improvements in mobility skills observed in this study adds to the evidence for the potential to progress despite persistent, severe deficits post-ABI. While participants made progress, this study did not examine whether rehabilitation addressed their postural alignment impairments. The effectiveness of therapy to improve postural alignment still needs to be investigated. Timed standing holding rails was the one measure where improvements were not statistically significant; measuring only to 30 seconds created a ceiling effect which limited the ability to demonstrate progress. Maintaining standing assists function and is one requirement to relearn walking, but evidence doesn’t yet demonstrate the relative priority of different aspects such as endurance, balance and alignment. Glasgow Coma Scale score has been used in many studies to evaluate outcome after ABI and was recorded as descriptive data for this study (Lu et al., 2015, Singh et al., 2013). Post-hoc analysis showed GCS scores did not correlate with COVS scores at baseline or six months, nor with discharge FIM scores. The statistically significant correlation with admission FIM scores provides a contrast, which could relate to admission FIM being the earliest measure recorded. Overall, it appears that GCS score in the first 24 hours after ABI did not relate to participants' functional outcomes.

These findings must be put into context of the limitations of the study. The small sample sizes influence generalisability of the results. Alignment of the COM of each body segment does not indicate segment angles, which can also influence function (Verheyden et al., 2014). Recording data for 30 seconds in participants' most upright alignment may not have fully demonstrated their postural issues, as they were recorded in their best, rather than their typical alignment. Postural alignment requires further evaluation of how it can best be analysed in clinical and research settings and also how it compares with other variables affecting physical function.

The ability to stabilise body segments in upright positions is a foundation requirement for much human function (van Dieen et al., 2018). The new, preliminary evidence for improved alignment relating to improved mobility after ABI aids understanding of biomechanical factors for progressing mobility skills. Improved mobility has important benefits to individuals and their families (Killington et al., 2010a), and also provides substantial societal benefits in terms of decreased costs of care (Turner-Stokes et al., 2019).

Chapter 6

Discussion, implications and directions for future research

6.1 Original contributions to knowledge

This thesis has drawn on previous evidence showing that mobility outcomes can be limited for people after ABI. Through expanding the understanding of what mobility impairment means to people after ABI, this research gives voice to the high priority that people with severe disability give to recovering mobility. Results have provided preliminary evidence for improvement in postural alignment being related to mobility outcome, potentially leading to an expanded understanding of the variables that warrant inclusion in clinical analysis and in kinematic research. Next, after reviewing the five primary aims of this research, key contributions to knowledge from this thesis are discussed in detail.

1) **Understand the significance of mobility for survivors of ABI with severe mobility impairment**

   This aim derived from the strong message in published research, and also in clinical practice, that people who fail to achieve a benchmark after ABI (such as independent walking) constitute a “fail”. Having a clear understanding of what matters to people with severe disability is critical to inform clinical practice, but also research, where the most complex cases are under-represented.

2) **Develop a valid, repeatable method of measuring whole-body postural alignment, suitable for people with severe postural issues**

   As no precedent was found for measurement of whole-body postural alignment, developing the PAD score method was a foundation requirement for the quantitative analysis.

3) **Determine if whole-body postural alignment is different after ABI, and if it becomes closer to healthy alignment over time**

   Verifying that alignment after ABI can differ from healthy adults was important as this was a foundation hypothesis for this research. Postural alignment becoming closer to healthy adults’ over time also supports the clinical concept being investigated.

4) **Establish changes made in mobility over 6 months in people with severe mobility impairment after ABI**

   This aim produced an important outcome in its own right and was essential for answering the next aim. Providing evidence for progress in complex cases is crucial to improve rehabilitation opportunities for adults with ABI.

5) **Determine what association exists between whole-body postural alignment and mobility over time following ABI**

   The primary aim for this thesis was to determine whether improvement in postural alignment is associated with mobility outcomes. This adds preliminary evidence for an additional variable that may influence mobility outcome after ABI.

Results from this thesis are now summarised into four key contributions from this research, which are listed here. Each one is expanded on in the sections below, and clinical implications of these are discussed. For people with severe mobility impairment after ABI:

- Improving mobility is crucial for wellbeing
- Postural alignment can be impaired, and can become closer to healthy alignment over time
- Significant progress over six months can be observed
- Sitting and standing postural alignment becoming more upright over the base of support is associated with improvements with mobility

6.2 Improving mobility is crucial for wellbeing in people with severe impairment after ABI

Prognosis for people with severe mobility impairment after ABI has often been reported as poor (Jorgensen et al., 1995, Craig et al., 2011). The frequency of severe mobility impairment after ABI is not known, partly as evaluation of people with severe impairments is limited, and partly as severe mobility impairment or non-ambulatory status is variably defined (Preston et al., 2011). However, it is known that many people do not recover independent walking after ABI (Preston et al., 2011).

The results in Chapter 2 demonstrate the importance of progress to people with severe mobility impairment after ABI. What their progress meant to participants makes it clear how critical physical improvements were for their wellbeing. This represents a challenge to the health system, when it is known that some people are denied admission to rehabilitation because of the severity of their impairments (Lynch et al., 2019, Luker et al., 2014). The poor outlook painted by some of the literature regarding people with severe deficits after ABI could suggest that they have little hope (Thorpe et al., 2018, Mees et al., 2016, Veerbeek et al., 2011, Willemse-van Son et al., 2007). The results in this thesis support that the provision of rehabilitation to people with severe deficits is important and worthwhile. These results also support that targeted research is needed to determine how outcomes for people with severe impairments can be improved. The impact of the frustrations that participants faced was magnified by the timeframes involved – each dealt with high levels of disability for months prior to and during the study. Despite the improvements they had made, participants were still striving to make progress six months after their first interviews. Interventions that achieve increased rate and amount of progress are a clear priority.

The qualitative finding that mobility achievements other than independent walking were important to participants is valuable to inform clinical practice. Results reminds clinicians of some of the aspects of mobility to consider with their patients and is informative when working with patients who are unable to communicate their preferences. It reinforces that outcomes that reduce dependence or improve dignity are important for those who do not achieve independent walking. This finding also presents challenges and opportunities for research. Many randomized controlled trials have restrictive inclusion criteria that mean the most complex cases are excluded (Moons et al., 2014). Research has had little focus on skills such as assisted standing, assisted walking, or transfers without a lifter as outcomes. However, the degree of importance placed on such aspects of progress by participants suggests that these require an evidence-base for interventions. As the timeframe to develop an evidence-base and achieve implementation into clinical practice can stretch into decades (Schliep et al., 2018), this could represent a substantial undertaking.

These results have also highlighted the challenge of how mobility outcomes after ABI can be better evaluated, to capture improvements that may not result in change on commonly used measures. Evaluation of the outcome of rehabilitation has typically included analysis of change in scores on standardized tools, such as the Functional Independence Measure (FIM) or Barthel Index (McLafferty et al., 2016, Hart et al., 2014, Fahey et al., 2018, Haffejee et al., 2013). Results in this thesis have indicated that standardized scales may not always reflect meaningful change for individuals. There has been a call for greater standardization of outcome measures in rehabilitation (Kwakkel et al., 2017, Wilde et al., 2010), which could bring benefit for areas such as meta-analyses. However, the limitations of some standardized measures such as inadequate responsiveness, floor effects and ceiling effects makes it challenging to identify measures that are appropriate across the wide range of skill levels seen after ABI (Stubbs et al., 2014, Appelros, 2007, Hobart et al., 2010, Levin et al., 2001).

6.2.1 Implications for research and ABI rehabilitation

The progress described by people who remained severely impaired with mobility at 8 weeks post-ABI adds an important illustration of improvements for complex cases. It provides further evidence that being severely impaired with mobility for many weeks after ABI does not rule out achieving meaningful improvement.

Improved knowledge of aspects of mobility that matter to people after ABI can be used to assist clinicians to tailor assessment and intervention. Patients with complex ABI typically have many deficits (Gagnon et al., 2005) and evidence needs to assist clinicians with prioritising aspects for attention. The amount of time spent standing and walking can be low after ABI (Sjöholm et al., 2014) and some rehabilitation interventions have a preponderance of activities in sitting and lying (Saeys et al., 2012). However, results in this thesis suggest that building skills in assisted standing and assisted walking was important for mobility progress, as well as for participants' sense of hope.

These results also indicate that evaluation of mobility outcome after ABI, particularly for those with severe impairments, cannot rely solely on standardized performance-based outcome measures. More responsive evaluation of outcome for those with severe disability is a priority for future research.

6.3 Postural alignment can be impaired after ABI, and can become closer to healthy alignment over time

With limited attention to postural alignment in previous kinematic studies, it has not been clear if impaired alignment normalises over time after ABI. The changes in postural alignment seen over time in this study, indicates that postural alignment becoming more upright over the base of support can be observed. The body segment distributions seen in healthy adults and adults with ABI supports that evaluating postural alignment can reveal considerable differences. This could have relevance to the findings in Chapter 2 that people felt self-conscious about how they looked and had a desire to feel more "normal".

There is a persistent challenge for research to refine methods of analysing kinematics that reflect the complexity of human function (Yun et al., 2014). Many studies have looked at kinematics in one plane, but as both sagittal and frontal issues occur (Feher-Kiss et al., 2018, Cretual, 2015), there is a limitation in applying results of single plane analysis to clinical practice. Therefore, it has been crucial for this study to reflect both frontal and sagittal plane deviations. While trunk and head have not been consistently included in kinematic studies (Roberts et al., 2017), they are obviously necessary inclusions to investigate the hypothesis in this thesis that whole-body alignment is associated with mobility outcome. My research postulates that it is clinically useful to analyse how multiple body parts align, rather than measure individual segments separately, which has been studied previously (Verheyden et al., 2014, Williams et al., 2009b).

It was also important for this study to analyse postural alignment in participants who could not maintain positions unsupported. There are numerous kinematic changes during tasks such as standing and walking after ABI (Chen et al., 2005, Williams et al., 2009b), but as the majority of evidence comes from analysis of independent tasks, there is limited understanding of kinematics of people who cannot stand and walk unassisted. While the severity of the kinematic changes that can occur in people who have lost independence could make such analysis seem crucial, there are significant barriers. The time-consuming impact of adding additional body segments to three-dimensional, motion-capture evaluation can be difficult (Gill et al., 2017, Huntley et al., 2017). Participants' ability to follow instructions and to tolerate the testing procedure may be more limited (Bartlett and Purdie, 2005). Participants requiring an assistant to complete tasks could obscure the cameras' views of retro-reflective markers, affecting the motion-capture recordings. There is also a challenge for the assistant to offer the skills required to assist the test optimally, and for assistance provided to be equivalent between participants (Butler et al., 2010). The research in this thesis used arm support via rails rather than help from an assistant, to manage these challenges. While this study did not specifically investigate the feasibility of kinematic evaluation of people with severe physical impairment, it is apparent that it was achieved in this sample, providing a basis for further related studies.

6.3.1 Implications for research and ABI rehabilitation

In clinical research, achieving a thorough picture of participants' changes may be aided by measuring postural alignment along with other physical variables such as muscle strength and balance. When postural alignment is impaired, attention to its improvement over time may assist understanding of physical recovery. In rehabilitation, postural alignment can be monitored over time via visual analysis, however, a clinical measure of postural alignment remains needed.

6.4 People with severe mobility impairment at eight weeks post-injury can make significant progress after ABI

Evidence clearly demonstrates that people who are non-ambulant after ABI can improve their function (Preston et al., 2011), however, studies reporting on outcomes for people who are not walking independently by 1-3 months post-ABI indicate they are unlikely to make further progress (Katz et al., 2004, Kwakkel and Kollen, 2013, Jorgensen et al., 1995). The findings in this thesis add to the evidence for people with severe deficits making progress. These results are not unprecedented, but are important additions to the evidence-base, particularly as participants in my study remained severely impaired with mobility for eight weeks following ABI. The level of detail generally provided in studies of outcome makes it difficult to interpret why research provides these varied findings. Studies that have investigated factors relating to mobility outcome have often looked at associations between a small number of baseline scores and mobility outcome (Craig et al., 2011). The range of factors relevant to mobility outcome has not been conclusively determined, but it is not clear that any study has analysed a full suite of variables relevant to mobility outcome. The many different measurement tools used, with varying psychometric properties, means studies may be measuring related but distinct constructs (Kwakkel et al., 2017). Further, the value of analysing change in variables over time versus measures at one time-point is not clear. Published descriptions of rehabilitation interventions also may lack the detail needed to compare studies (Hoffman 2014).

In this thesis, significant improvements on the Clinical Outcome Variables Scale (COVS), sit- to-stand, walking speed and the number of conditions achieved paints a positive picture of progress. Improvement in COVS, as a global measure, provides an indication of broad progress, rather than in an individual aspect of mobility. Sit-to-stand is a commonly measured aspect of mobility in rehabilitation, and the importance for participants of getting back on their feet (Chapter 2) supports its relevance. Improvement in walking speed is a widely used measure of walking capacity (Graham et al., 2008), and also fits with participants' comments about improvements to walking being important (Chapter 2). The number of conditions achieved is a unique measure to include, simply reflecting the number of sitting, standing and walking tasks that participants could perform to some extent. This was included as people with severe mobility impairment often have a low repertoire of functional skills and adding to the upright tasks that they can achieve has seemed a priority in the clinical setting. Its association with improved mobility in this study supports that exploring the number of upright, anti-gravity tasks that can be achieved by someone with severe mobility impairment is useful. Time of maintaining a standing position while holding on is also not typically used as a measure in research (Meyer et al., 2015). The lack of statistical significance of change in this measure suggests that a modified approach, such as adding alignment to time, may provide a better understanding of progress for those with severe disability after ABI.

6.4.1 Implications for research and ABI rehabilitation

Participants' improvement with mobility promotes that severe impairment at eight weeks post-ABI does not preclude progress. It raises further questions about the best way to evaluate prognosis, as predicting outcome after severe ABI remains uncertain (Husson et al., 2010).

There has been a call for rehabilitation to prescribe lower limb exercise more specifically for the biomechanical requirements of walking (Williams et al., 2019). The results in this thesis do not provide evidence for prescribing therapy that targets whole-body postural alignment, which would need to be investigated in an intervention trial. Results do provide a basis for such a trial, as they show that whole-body postural alignment and mobility tended to improve together in sitting and standing. There are many variables that can influence postural alignment, such as motor impairment, joint problems, pain and perceptual impairment of midline (Mansfield et al., 2015, Macedo Ribeiro et al., 2017). The results suggest that it could be relevant to investigate addressing various underlying causes of postural impairment.

6.5 Improving postural alignment in sitting and standing is associated with progress with mobility

The new evidence that improvement in whole-body postural alignment has an association with improving mobility after ABI supports the clinical hypothesis that has driven this project. The lack of evidence previously has meant that postural alignment has potentially been overlooked. Areas of research have investigated related concepts, including alignment of the whole-body centre of mass (COM) relative to the stance foot during walking (Lugade et al., 2011, Bruijn and van Dieen, 2018, Hurt et al., 2010, Gill et al., 2019). COM position reflects the relative motion of the body segments, which can be markedly impaired in pathological gait, although COM position does not differentiate between segment positions (Eames et al., 1999). COM position can provide an indication of the stability and energy efficiency of walking (Devetak et al., 2019). Similarly, the relationship between foot placement and pelvic displacement in the frontal plane has been described as crucial for walking efficiency (Stimpson et al., 2019). As the trunk and head are known to remain upright during healthy walking (Kavanagh et al., 2006), these models together are similar to the concept of whole-body alignment being relevant to walking performance. My studies have modelled body segments individually, as this is relevant to clinical assessment, which would need to identify the segments that are mal-aligned, to target intervention accordingly.

6.5.1 Implications for research and ABI rehabilitation

As improvement in whole-body postural alignment has been associated with progress with mobility, it indicates that clinical attention to whole-body alignment is warranted for people with mobility impairment. Results suggest that during clinical assessment after ABI, mobility skills and postural alignment should both be analysed, and changes described over time. As there are many elements to whole-body postural alignment, there is a need for research to identify the most critical aspects that could be key indicators in the clinical setting. Features seen in some participants such as the pelvis being behind the feet in standing provide examples that could be investigated.

6.6 Strengths and Limitations

While strengths of this thesis have already been portrayed in the relevant chapters, a further strength is that participants with ABI were studied in their inpatient rehabilitation setting. Motion-capture technology was set up onsite to facilitate access for complex cases who otherwise would have been unable to participate. While the aim was to maximise inclusion of people with severe mobility impairment, not all could be included, with the most frequent reason for exclusion being presence of complex impairments (inability to maintain sitting while holding rails and/or inability to follow instructions adequately). A quicker method of collecting data than 3D motion capture would be required to include more of these cases.

This research has focussed on people with severe mobility impairment at eight weeks post-ABI and did not include postural impairment as a criterion for inclusion, so may not have included all ABI survivors with postural issues. As there are many variables that influence mobility skills, people with impaired alignment could potentially improve other factors and progress with mobility without a change in alignment. Therefore, while results of this research put whole-body postural alignment "on the map" as a factor for recovering mobility, it has yet to be determined how postural alignment compares to other variables in terms of influencing mobility outcomes.

Elucidating the relationship and distinction between stability and posture is a challenge. Some studies present these as distinct entities, for example describing balance as postural stability and alignment as postural orientation, and these variables collectively as postural control (Dewar et al., 2014, Montecchi et al., 2013). Other studies do not make this distinction, for example, Pollock et al. (2007, p.396) defined postural control as "balance during the maintenance of a posture, restoration of a posture or movement between postures". Balance and alignment are related, as a change in postural alignment can affect balance (Iyengar et al., 2014). Balance appears to attract greater attention than alignment in the literature with several studies using the terms postural control and balance interchangeably (Chern et al., 2010, Sibley et al., 2015). Some studies that report on an investigation of "posture" have measured balance rather than alignment of body segments (Paillex and So, 2005, Perlmutter et al., 2010), indicating further differences in use of terms. Definitions of balance also vary, for example the ability to maintain and/or regain the centre of mass within the base of support (Dewar et al., 2014), or more simply, the dynamics of body posture to prevent falling (Winter, 1995). Balance can be measured by multiple laboratory methods including centre of pressure variations and patterns and movement of the centre of mass (Ruhe et al., 2010). Centre of pressure and whole-body centre of mass are related, so tend to change together (Piirtola et al., 2006). Centre of pressure measures derived from force plates provide an indication of muscle activity and deviations of the body over the base of support. Greater centre of pressure excursion has been associated with risk of falling in older adults (Piirtola et al., 2006). However, some evidence shows that greater centre of pressure excursions can be positively associated with stability in healthy adults, with lower variability in centre of mass and centre of pressure position associated with increased likelihood of a stepping response from perturbation (Rajachandrakumar et al., 2018). Applying some of these methods accurately to people with significantly impaired motor control can be a challenge (Havens et al., 2018), as these studies typically focus on participants who can stand or walk unsupported. Therefore, it is apparent that the extensive research into balance after ABI includes aspects of how the body relates to its base of support. Centre of pressure variations or deviations of the whole-body centre of mass could change with a variation to postural alignment, but do not indicate how individual body segments are aligned. During movement of body segments, it is possible for the position of the whole-body centre of mass to be fixed (Stapley et al., 2000). While the research in this thesis has assisted with demonstrating how body segments align posturally, questions remain about how changes to alignment influence stability in clinical populations.

This study has focussed on survivors of ABI with severe physical impairment, who could have been considered to have a relatively low likelihood of making significant progress, having not recovered ambulation by eight weeks post-injury. However, all were inpatients in an ABI rehabilitation facility. This study has not investigated the nature of mobility recovery or postural impairments for those who were not referred, or were rejected for inpatient rehabilitation. This would need to be investigated subsequently, for a complete picture of recovery of severe mobility impairment. Valuable evidence has come from the paediatric field, demonstrating that a high proportion of adults with cerebral palsy who have severe mobility impairment have postural deformity (Holmes et al., 2019). Research to investigate this in adults after ABI is needed.

The PAD score has not been psychometrically evaluated for its application to walking mid-stance. The differences in postural alignment during walking, and motor requirements to walk, may mean that the method for measurement may require modification. Walking mid-stance has greater postural complexity than standing, as the base of support changes continually, and in the frontal plane, the centres of mass of upper body segments remain medial to the foot in each mid-stance phase (Winter et al., 1991). While analysis of the segment position graphs (Figures 5.2 and 5.4) showed that in sitting and standing, body segments became closer to the base of support between baseline and 6 months, this trend was not obvious in the graphs for walking mid-stance. It has previously been found that combining measures of multiple segments in multiple planes during walking into a single robust measure can be difficult (Cabral et al., 2017). Further kinematic evaluation to describe postural alignment during walking is warranted. The definition of base of support was not modified when holding rails, which occurs in some studies; arm support on rails was considered to influence the participant's "supporting area" rather than the base of support (Härdi et al, 2014).

While using 3D kinematic data has enabled this thesis to measure postural alignment, the method used has limitations. Using the median frame of each segment's recording to measure postural alignment in sitting and standing could have masked the variability of participants. Variability of alignment of body segments during tasks such as sitting, standing and walking can be marked, for example in people with cerebellar impairment (Conte et al., 2014). Also, while the technology used provides excellent accuracy in demonstrating segment positions, it cannot show effort. Someone who achieves a certain alignment easily would have the same PAD score as someone who has marked difficulty while maintaining the same alignment. These details would be apparent during clinical evaluation and provides a reminder of the value of clinical analysis to accompany measurement.

6.7 Future work

There are many gaps in evidence for people with severe impairments after ABI that can be addressed through kinematic research, and potentially results in advances in rehabilitation. Evidence indicates that when analysing walking, clinicians do not consistently judge deficits accurately, and do not identify all impairments (Williams et al., 2009a). Therefore, using technology to extract data to add to clinician observations is important, and methods to do this quickly are required. Utilising new technologies may make this more readily achievable, such as deriving kinematic data more quickly from video recordings (Cao et al., 2019, Zult et al., 2019). There is a need for collaboration between health professionals in the clinical setting, health researchers skilled in applying research design to these cases, and biomechanists who can select and adapt methods for evaluating kinematics and also kinetics. A quicker method for measuring whole-body postural alignment could assist with including this variable routinely.

Impaired perception of midline after ABI is one factor that affects postural alignment that needs further investigation. A typical presentation when ABI causes motor impairment is asymmetry in sitting and standing, with greater loading on the less-affected side (Feher-Kiss et al., 2018). However, there were several examples in the participants with ABI of marked postural deviations towards the weaker side, which may be caused by perceptual impairment. After stroke, trunk tilt away from midline has been associated with reduced independence, supporting the concept that stabilising the trunk in midline is the optimal setting for posture (Piscicelli et al., 2016). Importantly, there is also evidence to show that trunk tilt toward the weaker side is associated with greater disability (Pérennou, 2008, Taylor et al., 1994). Clinically, this is a high priority to identify and address, but currently lacks an evidence base for it to receive clinical attention. Investigating a relationship between mobility impairment and trunk displacement towards the weaker side could lead to an update to clinical guidelines with more complete evaluation for the most complex cases.

While qualitative findings have given an indication of the personal value of progress with mobility for people with severe impairment after ABI, the broader impact of this change requires further investigation. Studies of carer burden have not tended to highlight issues with the physical load of caring (Lou et al., 2017). Studies exploring carer burden have not reported the level of mobility impairment of the care recipients, so it is not clear whether people with severe mobility impairment have been included. As the physical burden can be very high to care for someone with severe mobility impairment, this appears to be a key gap in evidence. Understanding the experience of caring for someone needing a high level of physical assistance, and the effect of improvements in their mobility on carer burden, will be important to inform clinical practice. As well as the physical demands of providing care, financial costs of care can be very high after ABI (Turner-Stokes et al., 2019). The change in long-term care costs that can occur when certain improvements with mobility are achieved requires an evidence base. Such evidence for cost savings can be used as a basis for funding delivery of rehabilitation. Long-term follow-up of mobility outcomes is needed within this research to accurately understand the lifetime costs associated with various levels of disability.

6.8 Conclusions

This thesis has identified that there are aspects of mobility that are high priorities for people with severe mobility impairment after ABI. The specific skills that were meaningful for participants provides a template for clinicians to consider, to assist with identifying interventions and targets that matter. How important “small” improvements were for participants’ wellbeing can potentially inform a shift in concept in rehabilitation research and possibly in some clinical settings. This finding demonstrates that while independent walking is highly sought after, progress that does not reach this target may still be important. The qualitative research findings can also assist health service delivery by helping clinicians to understand the frustration, vulnerability and despair that participants experienced when dependent with mobility. Significant improvements in mobility scores for a group of adults with ABI who were severely disabled at eight weeks post-injury adds to the evidence for progress of complex cases.

Application of three-dimensional kinematic analysis to adults with complex ABI is a unique achievement that offers great potential for further developments. Utilising the accuracy of kinematic data to develop the PAD score method of measuring whole-body postural alignment has allowed this research to generate new evidence that whole-body postural alignment has a relationship with improving mobility. This provides a basis for considering updates to clinical assessment in ABI rehabilitation, so that deviations of postural alignment are not missed. Clinical attention to mobility and postural alignment over time is also indicated, as these may occur together. Kinematic studies can consider including postural alignment as a variable for further analysis. Collectively, these results provide new information to advance kinematic research, and ABI rehabilitation.

Publications and presentations arising from this research

Peer-reviewed publication

Mills SJ, McDonnell MN, Thewlis D, Mackintosh S. Is there a relationship between postural alignment and mobility for adults after acquired brain injury? A systematic review. *Brain injury.* 2017;31(5):571-580.

Peer-reviewed conference presentations

2019 Mills SJ, Mackintosh S, McDonnell M, Thewlis D (2019). What is the relationship between change in postural alignment and mobility for adults after acquired brain injury? *Australian Physiotherapy Association Conference*. Adelaide, Australia.

2019 Mills SJ, Mackintosh S, McDonnell M (2019). What is the experience, and personal significance, of severe mobility impairment for adults with acquired brain injury? *Australian Physiotherapy Association Conference*. Adelaide, Australia.

2018 Mills SJ, Mackintosh S, McDonnell MN, Thewlis D (2018). Development of a measure for whole-body postural alignment in sitting, standing and walking (poster). *World Congress for NeuroRehabilitation*, Mumbai, India.

2017 Mills SJ, Mackintosh S, McDonnell MN, Thewlis D (2017). Development of a measure for whole-body postural alignment in sitting, standing and walking. *Australian Physiotherapy Association Conference*. Sydney, Australia.

2015 Mills SJ, Mackintosh S, Thewlis D, McDonnell MN (2015): Is there a relationship between postural alignment and mobility for adults after acquired brain injury? A systematic review. *Australian Physiotherapy Association Conference.* Gold Coast, Australia.

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Appendices

Statement of Authorship

Title of Paper	Improving physical mobility is critical for wellbeing in people with severe impairment after an acquired brain injury: a qualitative study
Publication Status	☐ Published ☐ Accepted for Publication ☑ Submitted for Publication Unpublished and Unsubmitted work written in manuscript style
Publication Details	Submitted to Journal of Physiotherapy

Principal Author

Name of Principal Author (Candidate)	Simon James Mills		
Contribution to the Paper	Conception and design of the research, data collection, data analysis, interpretation of results, drafting the manuscript, revising the manuscript, approving final version of the manuscript.		
Overall percentage (%)	80		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	12/8/2020

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Michelle McDonnell		
Contribution to the Paper	Design of the research, data collection, data analysis, interpretation of results, revising the manuscript, approving final version of the manuscript.		
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Name of Co-Author	Shylie Mackintosh		
Contribution to the Paper	Design of the research, data analysis, interpretation of results, revising the manuscript, approving final version of the manuscript.		
Signature		Date	18/8/2020

Statement of Authorship

Title of Paper	Is there a relationship between postural alignment and mobility for adults after acquired brain injury? A systematic review
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication Unpublished and Unsubmitted work written in manuscript style
Publication Details	Mills SJ, McDonnell MN, Thewlis D, Mackintosh S. Is there a relationship between postural alignment and mobility for adults after acquired brain injury? A systematic review. *Brain injury.* 2017;31(5):571-580. DOI: 10.1080/02699052.2017.1283061

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Contribution to the Paper	Conception and design of the research, performing the review, data analysis, interpretation of results, drafting the manuscript, revising the manuscript, approving final version of the manuscript.		
Overall percentage (%)	80		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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Contribution to the Paper	Design of the research, data analysis, interpretation of results, revising the manuscript, approving final version of the manuscript.		
Signature		Date	18/8/2020

Statement of Authorship

Title of Paper	Postural alignment is impaired in sitting and standing after complex acquired brain injury: an observational study		
Publication Status	☐ Published	☐ Accepted for Publication	
	☐ Submitted for Publication	Unpublished and Unsubmitted work written in manuscript style	
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Overall percentage (%)	80		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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Name of Co-Author	Michelle McDonnell		
Contribution to the Paper	Design of the research, data analysis, interpretation of results, revising the manuscript, approving final version of the manuscript.		
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Statement of Authorship

Title of Paper	Improvement in postural alignment in sitting and standing is associated with recovery of mobility after acquired brain injury: an observational study
Publication Status	☐ Published ☐ Accepted for Publication ☐ Submitted for Publication ☑ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Prepared for submission to Journal of Physiotherapy

Principal Author

Name of Principal Author (Candidate)	Simon James Mills		
Contribution to the Paper	Conception and design of the research, data collection, data analysis, interpretation of results, drafting the manuscript, revising the manuscript, approving final version of the manuscript.		
Overall percentage (%)	80		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	12/8/2020

Co-Author Contributions

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i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
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Name of Co-Author	Dominic Thewlis		
Contribution to the Paper	Design of the research, data analysis, interpretation of results, revising the manuscript, approving final version of the manuscript.		
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Contribution to the Paper	Design of the research, data analysis, interpretation of results, revising the manuscript, approving final version of the manuscript.		
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Contribution to the Paper	Design of the research, data analysis, interpretation of results, revising the manuscript, approving final version of the manuscript.		
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Approval Date: 19 May 2015

Mr Simon Mills
Brain Injury Rehabilitation Unit
Hampstead Rehabilitation Centre
207 Hampstead Road
NORTHFIELD SA 5085

Dear Mr Mills,

HREC reference number: **HREC/15/RAH/118**

Project Title**:** **"What is the relationship between severe mobility impairment and postural alignment for adults admitted to brain injury rehabilitation?"**

RAH Protocol No: 150414

Thank you for submitting the above project for ethical and scientific review. This project was first considered by the Royal Adelaide Hospital Human Research Ethics Committee at its meeting held on 23 April 2015.
I am pleased to advise that your protocol has been granted full ethics approval and meets the requirements of the *National Statement on Ethical Conduct in Human Research*. The documents reviewed and approved include:

- **NEAF Submission: AU/1/8F1E15. Site covered by this approval:**
    - Hampstead Rehabilitation Centre
- **Protocol Version 1, dated April 2015**
- **Participant Information Sheet, Version number 2, 27 April 2015**
- **Consent Form, Version number 2, 27 April 2015**
- **Interview Outline, Mobility after Severe ABI, Version 1, April 2015**
- **Data Sheet, Version 1, April 2015**
- **COVS – Clinical Outcome Variables Scale, Version 1, April 2015**
- **WHOQOL-BREF survey, Version 1, April 2015**

Please quote the **RAH Protocol Number, 150414** and the **HREC number, HREC/15/RAH/118** allocated to your study on all future correspondence.

GENERAL TERMS AND CONDITIONS OF ETHICAL APPROVAL:

- For all clinical trials, the study must be registered in a publicly accessible trials registry prior to enrolment of the first participant.
- Adequate record-keeping is important. If the project involves signed consent, you should retain the completed consent forms which relate to this project and a list of all those participating in the project, to enable contact with them in the future if necessary. The duration of record retention for all clinical research data is 15 years.
- You must notify the Research Ethics Committee of any events which might warrant review of the approval or which warrant new information being presented to research participants, including:
    (a) serious or unexpected adverse events which warrant protocol change or notification to research participants,
    (b) changes to the protocol,
    (c) premature termination of the study
- The Committee must be notified within 72 hours of any serious adverse event occurring at this site.
- Approval is valid for **5 years** from the date of this letter, after which an extension must be applied for. Investigators are responsible for providing an annual review to the RAH REC Executive Officer each anniversary of the above approval date, within 10 workings days, using the Annual Review Form available at: http://www.rah.sa.gov.au/rec/index.php
- The REC must be advised with a report or in writing within 30 days of completion.

Should you have any queries about the HREC's consideration of your project, please contact Mrs Heather O'Dea on 08 8222 4139, or rah.ethics@health.sa.gov.au .

Cont/2

You are reminded that this letter constitutes ethical approval only. You must not commence this research project at any site until separate authorisation from the Chief Executive or delegate of that site has been obtained.

This Committee is constituted in accordance with the NHMRC's *National Statement on the Ethical Conduct of Human Research* (2007).

The HREC wishes you every success in your research.

Yours sincerely,

A/Prof A Thornton
CHAIRMAN
RAH HUMAN RESEARCH ETHICS COMMITTEE

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19 October 2015

Mr Simon Mills
SA Brain Injury Rehabilitation Service
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207 Hampstead Road
Northfield, SA
5083

Dear Mr Mills

HREC reference number: HREC/15/RAH/118

SSA reference number: SSA/15/RAH/213

MyIP number (our reference): 5190

Project title: What is the relationship between severe mobility impairment and postural alignment for adults admitted to brain injury rehabilitation?

RE: Site Specific Assessment Review

Thank you for submitting an application for authorisation of this project. I am pleased to inform you that authorisation has been granted for this study to commence at the Hampstead Rehabilitation Centre, SA.

The following conditions apply to the authorisation of this research project. These are additional to those conditions imposed by the Human Research Ethics Committee that granted ethical approval to this project:

1. Authorisation is limited to the site/s identified in this letter only.
2. Project authorisation is granted for the term of your project outlined in Section 9 of the SSA, or until the project is complete (whichever date is earlier).
3. The study must be conducted in accordance with the conditions of ethical approval provided by the lead HREC, SA Health policies, and in conjunction with the standards outlined in the *National Statement on Ethical Conduct in Human Research* (2007) and the *Australian Code for the Responsible Conduct of Research* (*2007).*
4. Proposed amendments to the research protocol or conduct of the research which may affect the ethical acceptability of the project, and which are submitted to the HREC for review, are copied via email to this Research Governance Office;
5. Proposed amendments to the research protocol or conduct of the research which only affects the ongoing site acceptability of the project, are to be submitted via email to this Research Governance Office;
6. For all clinical trials, the study must be registered in a publicly accessible trials registry prior to enrolment of the first participant.
7. Proposed amendments to the research protocol or conduct of the research which may affect both the ongoing ethical acceptability of the project and the site acceptability of the project are to be submitted to this Research Governance Office after a HREC decision is made.
8. A copy of this letter should also be maintained on file by the Coordinating Principal Investigator as evidence of project authorisation.
9. Notification of completion of the study at this site is to be provided to this Research Governance Office.

If University personnel are involved in this project, the Principal Investigator should notify the University before commencing their research to ensure compliance with University requirements including any insurance and indemnification requirements.

We wish you every success in your research project.

Yours sincerely

Bernadette Swart
Manager, CALHN Research Office
Ph: 8222 3890
Email: bernadette.swart@sa.gov.au
Email: health.ResearchGovernanceIP&Contracts@sa.gov.au

Government of South Australia
SA Health

University of South Australia

School of Health Sciences

How does posture relate to mobility after acquired brain injury?

Participant Information Sheet

Researchers:
Simon Mills, Chief Investigator, phone 8222 1942
Dr Dominic Thewlis, phone 8302 1540
Dr Shylie Mackintosh, phone 8302 2075
Dr Michelle McDonnell, phone 8302 1684

Invitation to Participate

The participant is invited to take part in this study, which we believe could provide important information to understand how posture relates to mobility in people aged 18 and over who have survived a severe acquired brain injury. This is a research project and you do not have to be involved. If you do not wish to participate, your medical care will not be affected in any way. Also, you may withdraw from the project at any time after you have commenced.

What is the study about?

This study aims to record information about progress with mobility and about posture for people who aren't walking or have limited walking 8 weeks after their brain injury. For example, the study will look at how the head and trunk are positioned over the feet while standing. This will provide new information about how the body operates after brain injury.

What you would be asked to do:

Participants will undergo a series of tests at Hampstead Rehabilitation Centre:

Postural tests will use reflective markers, taped over a set number of points on the feet, knees, hips, pelvis, trunk, head and arms, for a computer to record the position of the body parts. The markers require participants to wear clothing such as sports bra / bike shorts / boxer shorts. Suitable clothing can be provided to participants if required. The testing area will be private when this data is being collected.
The postural tests will include sitting posture for all participants, maintaining the position for a maximum of 30 seconds. For those who can, standing and walking posture will also be recorded. Participants will hold on to parallel bars during the testing. For those who can, the postural tests will be repeated without holding on. The tests will be done 3 times.
Mobility tests will also be done, for comparison with the postural tests. These include tasks like rolling over in bed, standing up and walking, and which ones are included is based on what you agree to try.

A quality of life survey will be done with participants, with an interview to talk about changes since the brain injury. This will be used to look at how mobility skills relate to quality of life.
Height, weight and date of birth will be recorded.
The postural tests will be repeated on another day, within 4 days to assess consistency of the testing process.
The testing will be repeated 3 months and 6 months later, to look at progress following brain injury.

The time for the testing process will vary, and will take 60-90 minutes on average.

You can have someone with you, such as a family member, during the testing if you choose.

Video and photo will be taken of participants during some of the testing. This will be used for the purpose of studying the testing process. This footage will not be used for any other purpose unless the participant signs a separate, specific consent form.

The participant may withdraw from the research at any time at their discretion. If the researcher identifies an issue for any of the participants that may affect safe completion of the tests, they will help to manage the issue, or may withdraw that participant.

Possible benefits of participating:
Participants are not expected to benefit from taking part in the study. You will be contributing to the development of knowledge on this topic, which will be used to try to improve rehabilitation after acquired brain injury. Otherwise there are no anticipated benefits directly to you.

Possible Risks and Discomforts of Participating:
The testing could be strenuous if some of the tests are difficult to achieve. It will be spaced out as much as possible if this is needed.

Some people may find the quality of life part of the study stressful. Participants can choose to not complete some of these questions or any other part of the study if they're not comfortable.

If you discharge from Hampstead before completing the 3 month and 6 month measures, you will need to come back to Hampstead to complete these. Reasonable transport costs will be covered to help you to with this travel.

What if something goes wrong?

In the unlikely event that you suffer an injury through involvement in this study, care will be provided through the public hospital system. You should also be aware that indemnity of the study is provided through the Royal Adelaide Hospital.

What happens to the results?

All information collected as part of the study will remain confidential, and will only be available to the researchers listed on this form. No information which could lead to the identification of any individual will be released, unless required by law. Your personal results will be identified only with an identification number, not your name or details. All results will be stored securely; those on computer will be protected with a password, and a filing cabinet used for storage will be kept locked. Results will be retained for five years, as required by law. All participants who request a report explaining the results of the study will be emailed or posted a written report.

The results will be used as part of a Masters by Research thesis for the Chief Investigator.

What if I have a question?

You are welcome to direct your questions to Simon Mills at simon.mills@mymail.unisa.edu.au / 82221942, or if he is unavailable, to Dominic Thewlis.

The research will be conducted according to the NHMRC National Statement on Ethical Conduct in Human Research, 2007. If you wish to speak to someone not directly involved in the study about your rights as a volunteer, or about the conduct of the study, you may also contact the Chairperson, Research Ethics Committee, Royal Adelaide Hospital on 8222 4139.

Government of South Australia
SA Health
Hampstead Rehabilitation Centre

University of South Australia
UniSA **School of Health Sciences**

Project Title: How does posture relate to mobility after severe brain injury?

Researcher: Simon Mills

Contact Details: Simon.mills@mymail.unisa.edu.au; phone 82221942

Supervising Researchers: Dr Dominic Thewlis, Dr Shylie Mackintosh, Dr Michelle McDonnell

Contact Details: Dominic.Thewlis@unisa.edu.au

Participant Certification

Participant name:

In signing this form, I confirm that:

- I have read and understand the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.
- I have been advised of and understand the risks involved in participating in the project
- I understand that I am not expected to benefit from taking part in the project
- I understand that, while information gained during the study may be published, I will not be identified and my personal results will remain confidential, unless required by law.
- I understand that I can withdraw from the study at any stage and that this will not affect my medical care, now or in the future
- I have had the opportunity to discuss taking part in this study with a family member or friend
- If I am a guardian providing consent on behalf of the participant, I am confident that they are willing to participate.
- I understand that I will be videotaped during the testing
- I understand that all data including video files will be stored at Hampstead Rehabilitation Centre, and be accessible only to the researchers named above.
- I understand the statement in the information sheet concerning financial support for travel costs for the study, if this applies to me after discharge from Hampstead Rehabilitation Centre.

Participant / Guardian Signature	*Printed Name*	*Date*

Researcher Certification

I have explained the study to participants/guardian and consider that he/she understands what is involved.

Researcher Signature	*Printed Name*	*Date*

Simon James Mills

From: no_reply@unisa.edu.au
Sent: Monday, 30 November 2015 9:33 AM
To: Mills, Simon James - milsj004; Dominic Thewlis; Michelle McDonnell; Shylie Mackintosh; humanethics@unisa.edu.au
Subject: Human Ethics: Application approved

Dear Applicant

Re: Ethics protocol "What is the relationship between severe mobility impairment and postural alignment for adults admitted to brain injury rehabilitation?" (Application ID: 0000035040)

Thank you for submitting your ethics protocol for consideration. Your protocol has been considered by the E1 Committee Review Group.

I am pleased to advise that your protocol has been granted ethics approval and meets the requirements of the National Statement on Ethical Conduct in Human Research. Please note that the E1 Committee Review Group's decision will be reported to the next meeting of the Human Research Ethics Committee for endorsement.

Please regard this email as formal notification of approval.

Ethics approval is always made on the basis of a number of conditions detailed at http://www.unisa.edu.au/res/forms/docs/humanresearchethics_conditions.doc; it is important that you are familiar with, and abide by, these conditions. It is also essential that you conduct all research according to UniSA guidelines, which can be found at http://www.unisa.edu.au/res/ethics/default.asp

Please note, if your project is a clinical trial you are required to register it in a publicly accessible trials registry prior to enrolment of the first participant (e.g. Australian New Zealand Clinical Trials Registry http://www.anzctr.org.au/) as a condition of ethics approval.

Best wishes for your research.

Executive Officer
UniSA's Human Research Ethics Committee CRICOS provider number 00121B

This is an automated email and cannot be replied to. Please direct your query to humanethics@unisa.edu.au.

UniSA

University of South Australia

School of Health Sciences

What is posture like during sitting, standing and walking for healthy adults?

Participant Information Sheet

Researchers:

Simon Mills, B. Physiotherapy, phone 8222 1942

Dominic Thewlis, PhD, phone 8302 1540

Shylie Mackintosh, PhD

Michelle McDonnell, PhD

Invitation to Participate

You are invited to take part in this study, which we believe could provide important information to understand posture in healthy people aged 18 and over, with no history of neurological illness, or physical limitations affecting mobility. Participation is voluntary. The following information is provided to help you decide if you will participate. If you decide to participate and change your mind, you are free to withdraw at any time.

What is the study about?

This study aims to record the posture of body parts during sitting, standing and walking, in healthy adults. For example, how the head, trunk and pelvis are positioned over the feet while standing. This will provide new information about how the body operates in healthy people, to compare with people with physical limitations. This may eventually lead to a new understanding of whether posture correlates with function for people with physical limitations.

What you would be asked to do:

Participants will undergo a series of postural tests in the Biomechanics Lab at the University of South Australia, City East campus. Height, weight and date of birth will be recorded.

The postural tests will use reflective markers, taped over a set number of points on the feet, knees, hips, pelvis, trunk, head and arms, for a computer to record the position of the body parts. The reflective markers require participants to wear clothing that won’t affect the body markers, such as crop top/bike shorts. Suitable clothing can be provided to participants if required. The testing area will be private when this data is being collected.

The testing process will take about an hour, and will be done twice, requiring attendance on two separate days, up to 7 days apart.

Video footage will be taken of participants during some of the testing. This will be used for the purpose of assessment of the testing process. Video footage will not be used for any other purpose unless the participant signs a talent release form.

The participant may withdraw from the research at any time at their discretion. If the researcher identifies an issue for any of the participants that may affect safe completion of the tests, they will help to manage the issue, or initiate that participant withdrawing.

Possible benefits of participating:

You will be contributing to the development of knowledge on this topic; otherwise there are no anticipated benefits directly to you.

Participants will be entitled to receive a $20 gift card after the testing sessions, in recognition of their time and any potential costs such as travel costs.

Possible risks of participating:

There are no anticipated risks of involvement.

What happens to the results?

All information collected as part of the study will remain confidential, and will only be available to the researchers listed on this form. No information which could lead to the identification of any individual will be released, unless required by law. Your personal results will be identified only with an identification number, not your name or details. All results will be stored securely; those on computer will be protected with a password, and a filing cabinet used for storage will be kept locked. Results will be retained for five years, as required by law. All participants who request a report explaining the results of the study will be emailed or posted a written report.

What if I have a question?

You are welcome to direct your questions to Simon Mills at simon.mills@mymail.unisa.edu.au / 82221942, or if he is unavailable, to Dominic Thewlis. The other researchers involved in this project are Shylie Mackintosh and Michelle McDonnell.

This project has been approved by the University of South Australia's Human Research Ethics Committee. If you have any ethical concerns about the project or questions about your rights as a participant please contact the Executive Officer of this Committee, Tel: +61 8 8302 3118; Email: vicki.allen@unisa.edu.au

Research and
Innovation Services

Human Research Ethics Committee

CONSENT FORM

Use this consent form when taped materials, photographs or original works are to be retained

This project has been approved by the University of South Australia's Human Research Ethics Committee. If you have any ethical concerns about the project or questions about your rights as a participant please contact the Executive Officer of this Committee, Tel: +61 8 8302 3118; Email: Vicki.Allen@unisa.edu.au

Researcher: Simon Mills

Contact Details: Simon.mills@mymail.unisa.edu.au; phone 82221942

Supervisor: Dr Dominic Thewlis

Contact Details: Dominic.Thewlis@unisa.edu.au

Protocol Number: 33756

Project Title: What is posture like during sitting, standing and walking for healthy adults?

Participant Certification

In signing this form, I confirm that:

- I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.
- I understand the purpose of the research project and my involvement in it.
- I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.
- I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential, unless required by law.
- I understand that I will be videotaped during the testing.
- I understand that all data including video files will be stored in the International Centre for Allied Health Evidence at the University of South Australia, and be accessible only to the researcher named above, and to the project's three supervisors.
- I understand the statement in the information sheet concerning the offer of a gift card to me for taking part in the study.

Participant Signature	*Printed Name*	*Date*

Researcher Certification

I have explained the study to subject and consider that he/she understands what is involved.

Researcher Signature	*Printed Name*	*Date*

Clinical Outcome Variables Scale (COVS)

Participant no:

Ax date:	
ITEM 1: ROLL TO (R) SIDE IN BED 1= fully dependent two assistants required 2= 1 person assistance with or without device 3= 1 person assistance no device * 4= rolls by self but needs assistance for final position (getting comfortable) 5= independent with device 6= independent without device awkward and requires more effort 7= independent, no effort, coordinated and efficient	1 2 3 4 5 6 7
ITEM 2: ROLL TO (L) SIDE IN BED 1= fully dependent two assistants required 2= 1 person assistance with or without device 3= 1 person assistance no device * 4= rolls by self but needs assistance for final position(getting comfortable) 5= independent with device 6= independent without device awkward and requires more effort 7= independent, no effort, coordinated and efficient	1 2 3 4 5 6 7
ITEM 3: GETS TO A SITTING POSITION FROM SUPINE LYING IN BED 1= fully dependent two assistants required 2= One person assistance (with or without device) 3= 1 person assistance no device * 4= needs supervision /instruction for safety may use device 5= independent with device 6= independent without device, but slow, awkward, more effort 7= independent no effort, coordinated and efficient	1 2 3 4 5 6 7
ITEM 4: SITTING BALANCE Testing position: Edge of bed, feet on floor, arms folded across chest, not wearing prosthesis 1= not able to sit unsupported 2= able to sit unsupported (10 seconds) 3= able to move head and trunk within base 4= able to lift arm and leg within base of support * 5= move beyond base and return 6= tolerates external displacement- slow reactions 7= tolerates external displacement efficient reactions	1 2 3 4 5 6 7
ITEM 5: HORIZONTAL TRANSFER (best side slide/ pivot depending on client's ability) 1= fully dependent in either type of transfer- requires 2 assistants 2= needs one person assistance and a device (eg sliding board) 3= assistance /no need for device 4= supervision/ instructions with or without an assistive device 5= independent with device (eg sliding board) 6= independent, slow, awkward, requires more effort, no device 7= independent, no effort, coordinated and efficient	1 2 3 4 5 6 7
ITEM 6: VERTICAL TRANSFER Floor-chair/floor-to-stand firm or soft surface 1= dependent- requires two assistants or hoist 2= 1 person assistance with device (eg chair) 3= 1 person assistance without device 4= supervision/instructions with or without device 5= independent with / without device requires effort ,slow 6= independent stands up on firm surface, no device slow, awkward, effort 7= independent stands up soft surface no effort, coordinated and efficient	1 2 3 4 5 6 7
ITEM 7: PERFORMANCE OF AMBULATION 1= Non functional ambulation, in rails only, or ≥ 2 assist outside rails 2= 1 person continuous physical assistance 3= 1 person intermittent assistance 4= supervision required with verbal cues for safety 5= independent level surfaces only, assistance with other surfaces and stairs 6= independent with all surfaces, stairs require a rail 7 = efficient ambulation ,normal speed, stairs without a rail	1 2 3 4 5 6 7

ITEM 8:PERFORMANCE OF AMBULATION –USE OF WALKING AIDS		
1= not walking	1	
2= parallel bars required or 2 person continuous assist	2	
3= walking frame	3	
4= 2 aids – eg 2crutches or 4 point sticks	4	
5= uses 1 crutch or 1 4-point stick	5	
6= uses single cane only	6	
7= walks without an aid	7	
ITEM 9: PERFORMANCE OF AMBULATION – ENDURANCE		
1= not walking	1	
2= walks < 10 metres (6m in parallel bars)	2	
3= walks 10m < 50 metres	3	
4= walks 51m <100m	4	
5= walks 101m < 200m *	5	
6= walks 201m < 500m	6	
7= walks > 500m	7	
ITEM 10: PERFORMANCE OF AMBULATION- SPEED OVER 10 M		
1= not walking	1	
2= walks <0.1m/sec	2	
3= walks < 0.3 m/sec	3	
4= walks <0.5m/sec *	4	
5= walks <0.7m/sec	5	
6= walks <0.9m/sec	6	
7= walks > 0.9m/sec	7	
ITEM 11: PERFORMANCE OF WHEELCHAIR MOBILITY		
1= fully dependent	1	
2= able to move chair < 10 m (requires assistance)	2	
3= able to move chair < 30 m (requires assistance)	3	
4= supervision only required on flat surfaces, assistance for barriers (eg doors)	4	
5= independent indoors all surfaces manages doors	5	
6= independent outdoors excluding curbs and grass	6	
7= independent outdoors, all surfaces and conditions	7	
ITEMS 12 and 13: ARM FUNCTION (each arm scored separately)	L	R
1= unable to move actively any part of the arm	1	1
2= some active movement , nothing useful	2	2
3= able to use arm as a stabiliser in weight bearing; other arm assists it	3	3
4=able to use arm as stabiliser in function-eg hold jar while remove lid other hand; some	4	4
movement eg hand to mouth	5	5
5= able to bring a cup of water to the mouth; has proximal and distal movt	6	6
6= functional including fine movements but clumsy and awkward(buttons)	7	7
7= normal –efficient fine motor skill (eg picks up coins and posts in money box quickly		
	Total	/91

Sit to stand

	Date:			
	Scores:			
	Chair/height:			
	Device:			
7	Stands up from a regular chair safely			
6	Requires device, or takes an unreasonable amount of time			
5	Supervision			
4	Minimal assistance Performs 75% or more			
3	Moderate assistance Performs 50-74%			
2	Maximal Assistance Performs 25-49%			
1	Total Assistance Performs <25%			
0	Activity does not occur			

Chapter 2: Consolidated criteria for reporting qualitative studies (COREQ): 32-item checklist

Developed from:
Tong A, Sainsbury P, Craig J. Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care*. 2007. Volume 19, Number 6: pp. 349 – 357

No. Item	Guide questions/description	Reported on Page #
Domain 1: Research team and reflexivity		
Personal Characteristics		
1. Inter viewer/facilitator	Which author/s conducted the inter view or focus group?	12
2. Credentials	What were the researcher's credentials? E.g. PhD, MD	12
3. Occupation	What was their occupation at the time of the study?	12
4. Gender	Was the researcher male or female?	N/A
5. Experience and training	What experience or training did the researcher have?	12
Relationship with participants		
6. Relationship established	Was a relationship established prior to study commencement?	N/A
7. Participant knowledge of the interviewer	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	N/A
8. Interviewer characteristics	What characteristics were reported about the inter viewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	22
Domain 2: study design		
Theoretical framework		
9. Methodological orientation and Theory	What methodological orientation was stated to underpin the study? e.g. grounded theory, discourse analysis, ethnography, phenomenology, content analysis	11
Participant selection		
10. Sampling	How were participants selected? e.g. purposive, convenience, consecutive, snowball	11
11. Method of approach	How were participants approached? e.g. face-to-face, telephone, mail, email	11
12. Sample size	How many participants were in the study?	14
13. Non-participation	How many people refused to participate or dropped out? Reasons?	14

Setting		
14. Setting of data collection	Where was the data collected? e.g. home, clinic, workplace	12
15. Presence of non-participants	Was anyone else present besides the participants and researchers?	12
16. Description of sample	What are the important characteristics of the sample? e.g. demographic data, date	11
Data collection		
17. Interview guide	Were questions, prompts, guides provided by the authors? Was it pilot tested?	13
18. Repeat interviews	Were repeat inter views carried out? If yes, how many?	14
19. Audio/visual recording	Did the research use audio or visual recording to collect the data?	12
20. Field notes	Were field notes made during and/or after the inter view or focus group?	12
21. Duration	What was the duration of the inter views or focus group?	14
22. Data saturation	Was data saturation discussed?	13
23. Transcripts returned	Were transcripts returned to participants for comment and/or correction?	12
Domain 3: analysis and findings		
Data analysis		
24. Number of data coders	How many data coders coded the data?	13
25. Description of the coding tree	Did authors provide a description of the coding tree?	15
26. Derivation of themes	Were themes identified in advance or derived from the data?	13
27. Software	What software, if applicable, was used to manage the data?	13 (NVivo)
28. Participant checking	Did participants provide feedback on the findings?	N/A
Reporting		
29. Quotations presented	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g. participant number	14-20
30. Data and findings consistent	Was there consistency between the data presented and the findings?	14-22
31. Clarity of major themes	Were major themes clearly presented in the findings?	14-20
32. Clarity of minor themes	Is there a description of diverse cases or discussion of minor themes?	16

PRISMA 2009 Checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	24
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	24
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	25-27
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	27
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	27
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	27-29
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	27
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	28
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	29
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	29
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	33-34
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	41
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	N/A
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	N/A
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	41
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	30
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	33-34

Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	N/A
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	N/A
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	N/A
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	36
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	41
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	41
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	N/A

From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

PROSPERO International prospective register of systematic reviews

Review title and timescale

1 Review title
Give the working title of the review. This must be in English. Ideally it should state succinctly the interventions or exposures being reviewed and the associated health or social problem being addressed in the review.
Is there a relationship between postural alignment and mobility for adults after Acquired Brain Injury? A systematic review.

2 Original language title
For reviews in languages other than English, this field should be used to enter the title in the language of the review. This will be displayed together with the English language title.

3 Anticipated or actual start date
Give the date when the systematic review commenced, or is expected to commence.
27/04/2015

4 Anticipated completion date
Give the date by which the review is expected to be completed.
31/07/2015

5 Stage of review at time of this submission
Indicate the stage of progress of the review by ticking the relevant boxes. Reviews that have progressed beyond the point of completing data extraction at the time of initial registration are not eligible for inclusion in PROSPERO. This field should be updated when any amendments are made to a published record.

The review has not yet started ☒

Review stage	Started	Completed
Preliminary searches	Yes	No
Piloting of the study selection process	No	No
Formal screening of search results against eligibility criteria	No	No
Data extraction	No	No
Risk of bias (quality) assessment	No	No
Data analysis	No	No

Provide any other relevant information about the stage of the review here.

Review team details

6 Named contact
The named contact acts as the guarantor for the accuracy of the information presented in the register record.
Simon Mills

7 Named contact email
Enter the electronic mail address of the named contact.
millsysj@hotmail.com

8 Named contact address
Enter the full postal address for the named contact.
SA Brain Injury Rehabilitation Services 207 Hampstead Road Northfield SA 5085 Australia

9 Named contact phone number
Enter the telephone number for the named contact, including international dialing code.
+61 8 82221942

10 Organisational affiliation of the review
Full title of the organisational affiliations for this review, and website address if available. This field may be completed as 'None' if the review is not affiliated to any organisation.

University of South Australia

Website address:
www.unisa.edu.au

11 Review team members and their organisational affiliations

Give the title, first name and last name of all members of the team working directly on the review. Give the organisational affiliations of each member of the review team.

Title	First name	Last name	Affiliation
Mr	Simon	Mills	Masters by Research Candidate
Dr	Shylie	Mackintosh	Program Director, Physiotherapy
Dr	Michelle	McDonnell	Senior Lecturer, Physiotherapy
Dr	Dominic	Thewlis	Senior Lecturer, Human Movement

12 Funding sources/sponsors

Give details of the individuals, organizations, groups or other legal entities who take responsibility for initiating, managing, sponsoring and/or financing the review. Any unique identification numbers assigned to the review by the individuals or bodies listed should be included.

Hampstead Rehabilitation Centre and University of South Australia are supporting the review

13 Conflicts of interest

List any conditions that could lead to actual or perceived undue influence on judgements concerning the main topic investigated in the review.

Are there any actual or potential conflicts of interest?

None known

14 Collaborators

Give the name, affiliation and role of any individuals or organisations who are working on the review but who are not listed as review team members.

Title	First name	Last name	Organisation details

Review methods

15 Review question(s)

State the question(s) to be addressed / review objectives. Please complete a separate box for each question.

Is there a relationship between postural alignment and mobility for adults after Acquired Brain Injury?

16 Searches

Give details of the sources to be searched, and any restrictions (e.g. language or publication period). The full search strategy is not required, but may be supplied as a link or attachment.

These databases will be searched electronically: EMBASE, Scopus, MEDLINE, CINAHL, Web of Science, Cochrane Library, Informit, Google scholar.

17 URL to search strategy

If you have one, give the link to your search strategy here. Alternatively you can e-mail this to PROSPERO and we will store and link to it.

I give permission for this file to be made publicly available

No

18 Condition or domain being studied

Give a short description of the disease, condition or healthcare domain being studied. This could include health and wellbeing outcomes.

Postural alignment - the alignment of body parts in an upright position (including trunk or head position)

19 Participants/population

Give summary criteria for the participants or populations being studied by the review. The preferred format includes

details of both inclusion and exclusion criteria.
Inclusion criteria: • Participants are adults with acquired brain injury, including stroke, traumatic brain injury and hypoxic brain injury Exclusion criteria: • Degenerative conditions such as multiple sclerosis, Parkinson's disease

20 Intervention(s), exposure(s)
Give full and clear descriptions of the nature of the interventions or the exposures to be reviewed
None

21 Comparator(s)/control
Where relevant, give details of the alternatives against which the main subject/topic of the review will be compared (e.g. another intervention or a non-exposed control group).
Posture will be compared against a measure of mobility, such as standing up or walking.

22 Types of study to be included initially
Give details of the study designs to be included in the review. If there are no restrictions on the types of study design eligible for inclusion, this should be stated.
All study designs will be included.

23 Context
Give summary details of the setting and other relevant characteristics which help define the inclusion or exclusion criteria.
Any study of an acquired brain injury cohort could be eligible, as long as it contains a measure of postural alignment, and a measure of mobility.

24 Primary outcome(s)
Give the most important outcomes.
Relationship between posture and an aspect of mobility

Give information on timing and effect measures, as appropriate.

25 Secondary outcomes
List any additional outcomes that will be addressed. If there are no secondary outcomes enter None.
None

Give information on timing and effect measures, as appropriate.

26 Data extraction, (selection and coding)
Give the procedure for selecting studies for the review and extracting data, including the number of researchers involved and how discrepancies will be resolved. List the data to be extracted.
Titles and abstracts will be reviewed by the chief investigator, potentially eligible publications will be shortlisted. Shortlisted studies will be checked by two investigators, including full-text when required. Any disagreements will be resolved by consultation with a third investigator. Included studies will also have reference lists checked for other studies to be included.

27 Risk of bias (quality) assessment
State whether and how risk of bias will be assessed, how the quality of individual studies will be assessed, and whether and how this will influence the planned synthesis.
Included studies will be rated using the NHMRC Levels Of Evidence. A final decision on what levels of evidence to include in the analysis will be made after the included studies are determined.

28 Strategy for data synthesis
Give the planned general approach to be used, for example whether the data to be used will be aggregate or at the level of individual participants, and whether a quantitative or narrative (descriptive) synthesis is planned. Where appropriate a brief outline of analytic approach should be given.
Qualitative synthesis is planned. Data will be reported according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

29 Analysis of subgroups or subsets
Give any planned exploration of subgroups or subsets within the review. ‘None planned’ is a valid response if no subgroup analyses are planned.

None planned.

Review general information

30 Type of review
Select the type of review from the drop down list.
Other

Observational

31 Language
Select the language(s) in which the review is being written and will be made available, from the drop down list. Use the control key to select more than one language.
English

Will a summary/abstract be made available in English?
Yes

32 Country
Select the country in which the review is being carried out from the drop down list. For multi-national collaborations select all the countries involved. Use the control key to select more than one country.
Australia

33 Other registration details
Give the name of any organisation where the systematic review title or protocol is registered together with any unique identification number assigned. If extracted data will be stored and made available through a repository such as the Systematic Review Data Repository (SRDR), details and a link should be included here.

34 Reference and/or URL for published protocol
Give the citation for the published protocol, if there is one.
Give the link to the published protocol, if there is one. This may be to an external site or to a protocol deposited with CRD in pdf format.

I give permission for this file to be made publicly available
No

35 Dissemination plans
Give brief details of plans for communicating essential messages from the review to the appropriate audiences.
As well as publication, results will be communicated through conference presentations.

Do you intend to publish the review on completion?
Yes

36 Keywords
Give words or phrases that best describe the review. (One word per box, create a new box for each term)
Postural alignment

Mobility

Acquired Brain Injury

37 Details of any existing review of the same topic by the same authors
Give details of earlier versions of the systematic review if an update of an existing review is being registered, including full bibliographic reference if possible.

38 Current review status
Review status should be updated when the review is completed and when it is published.
Ongoing

39 Any additional information

Provide any further information the review team consider relevant to the registration of the review.

40 Details of final report/publication(s)

This field should be left empty until details of the completed review are available.
Give the full citation for the final report or publication of the systematic review.
Give the URL where available.

Chapter 4: STROBE checklist

	Item No	Recommendation	Page number
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	45
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	45
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	47
Objectives	3	State specific objectives, including any prespecified hypotheses	47
Methods			
Study design	4	Present key elements of study design early in the paper	48
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	48
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	48
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	51
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	48-51
Bias	9	Describe any efforts to address potential sources of bias	
Study size	10	Explain how the study size was arrived at	
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	52
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	
		(*e*) Describe any sensitivity analyses	

Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	54
		(b) Give reasons for non-participation at each stage	54
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	54
		(b) Indicate number of participants with missing data for each variable of interest	
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	53-54
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	
		Cross-sectional study—Report numbers of outcome events or summary measures	
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	54
		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	54
Discussion			
Key results	18	Summarise key results with reference to study objectives	60
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	61
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	62
Generalisability	21	Discuss the generalisability (external validity) of the study results	61
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Acknowledgements

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

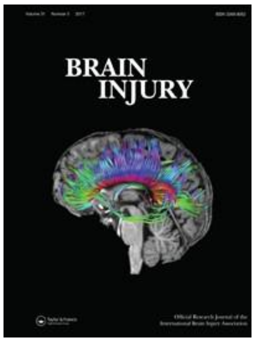
Chapter 5: STROBE checklist

	Item No	Recommendation	Page number
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	70
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	71
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	72
Objectives	3	State specific objectives, including any prespecified hypotheses	73
Methods			
Study design	4	Present key elements of study design early in the paper	72-74
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	73
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	73
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	73-75
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	74-75
Bias	9	Describe any efforts to address potential sources of bias	N/A
Study size	10	Explain how the study size was arrived at	N/A
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	75
		(*b*) Describe any methods used to examine subgroups and interactions	
		(*c*) Explain how missing data were addressed	74
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	
		(*e*) Describe any sensitivity analyses	

Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	75
		(b) Give reasons for non-participation at each stage	75, 77
		(c) Consider use of a flow diagram	
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	72
		(b) Indicate number of participants with missing data for each variable of interest	77
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	77
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	
		Cross-sectional study—Report numbers of outcome events or summary measures	
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	75
		(*b*) Report category boundaries when continuous variables were categorized	
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	79
Discussion			
Key results	18	Summarise key results with reference to study objectives	85
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	86
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	85
Generalisability	21	Discuss the generalisability (external validity) of the study results	87
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Acknowledgements

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.



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REVIEW ARTICLE

Is there a relationship between postural alignment and mobility for adults after acquired brain injury? A systematic review

Simon J. Mills [a,b], Michelle N. McDonnell [c], Dominic Thewlis [c], and Shylie Mackintosh [d]

[a]South Australian Brain Injury Rehabilitation Service, Hampstead Rehabilitation Centre, Adelaide, SA, Australia; [b]International Centre for Allied Health Evidence (iCAHE); [c]Alliance for Research in Exercise, Nutrition and Activity (ARENA); [d]Sansom Institute for Health Research, University of South Australia, Adelaide, SA, Australia

ABSTRACT

Primary objective: To examine the relationship between postural alignment and mobility skills for adults after acquired brain injury (ABI).

Methods: Systematic review of the literature. Seven electronic databases, grey literature and reference lists of the shortlisted publications were searched. Studies were included if participants were adults with ABI, both postural alignment and mobility were measured and analysis included a relationship between alignment and mobility. Those that met the inclusion criteria were assessed with a critical appraisal tool. The review was registered with PROSPERO, registration number CRD42015019867.

Results: Seven observational studies were included that had examined a relationship between postural alignment and mobility after ABI. Critical appraisal scores were moderate to strong. While some studies reported that improved postural alignment was related to improved mobility after ABI, results varied and there was insufficient evidence to answer the primary question. Heterogeneous study designs did not allow meta-regression.

Conclusions: A small amount of observational evidence exists for a relationship between postural alignment and mobility after ABI. Results vary, with some studies reporting that a more stable, upright trunk correlates with better mobility, and others providing conflicting or ambiguous results. Further research is needed to establish the relationship between postural alignment and mobility skills after ABI.

ARTICLE HISTORY
Received 23 June 2016
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KEYWORDS
Head injury; stroke; trunk; posture; walking; standing

Introduction

Mobility impairment is a highly disabling effect of acquired brain injury (ABI) in adults [1,2]. The aetiology of ABI is diverse, and can include stroke, traumatic brain injury (TBI) and other non-traumatic injuries such as hypoxia [3]. ABI often results in a high cost to the health system in the first weeks and months, with long acute and sub-acute hospital lengths of stay [4,5]. However, physical limitations that result from ABI may continue for decades and relate to life-long restrictions in lifestyle [6,7]. The impact of ABI is wide-reach- ing, with 2.2% of the adult population having ABI-related disability [3]. Survivors of ABI can have marked changes in independence, relationships, ability to achieve employment and ultimately in self-concept [8–11]. The burden on family carers of adults with ABI can be very high, including psycho- logical stress and social isolation [12,13]. The magnitude of the impact of ABI emphasises the importance of research to enhance outcomes and quality of life for survivors.

Mobility has been described broadly as a person's independence in moving about the home or community [14], and specifically as discrete skills such as walking and climbing stairs [15,16]. Walking is commonly rated as the highest priority for people surviving ABI [17,18], and improved mobility after ABI has been shown to correlate with improved quality of life [1,19]. Multiple factors have been identified that relate to limited mobility after ABI, such as reduced muscle strength [20–23], reduced muscle power [24,25], reduced cardiovascular fitness [26], balance impairment [27–29], cognitive impairment [30–32] and reduced balance confidence [33,34]. In biomechanical studies, factors that have correlated with improved walking performance after ABI include less lateral pelvic displacement [35–37], and greater ankle power generation at push-off [38,39]. Upper body alignment has been given very little attention in biomechanical studies of walking [40,41], despite the large volume of research undertaken. During preparation of this publication, a brief search of Scopus and Web of Science for biomechanical studies of walking after brain injury showed high yield with over 2000 titles, yet the present review found that almost all biomechanical studies focussed exclusively on the legs. While it has been demonstrated that a stable, upright trunk is a key feature of healthy walking [41–43], the upper body is rarely examined in studies of mobility after ABI. A similar trend of a lack of data collection on the upper body, and lack of analysis of upper body data, has also been reported in other areas of research with neurological conditions, such as cerebral palsy [44].

Several studies have compared the upper body during mobility after ABI with healthy adults. Trunk flexion was significantly greater during walking in people with TBI compared with healthy adults, with no significant difference in lateral flexion [45]. This

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study demonstrated many important features of walking after TBI, including a high prevalence of pelvic and trunk abnormalities, but did not examine a relationship between alignment data and mobility data. Verheyden et al. [46] evaluated spinal alignment and found that the participants with stroke had significantly more forward inclination of the trunk than the healthy control group during standing. They reported that in the participants with stroke, more forward inclination of the trunk during standing correlated with lower scores on the Berg Balance Scale, indicating that the more upright participants performed better on that test. Trunk symmetry has also been evaluated in a group of survivors of stroke; those who showed trunk deviation towards their weaker side during sitting scored significantly lower on mobility using the Rivermead Mobility Assessment at 3 and 6 weeks following stroke [47]. Presence of unilateral neglect correlated significantly with trunk deviation towards the weaker side.

Several studies have also compared the performance of trunk muscles in healthy adults with people after stroke. Significant differences have been shown in the timing and rate of force development in trunk muscles during movement [48–50]. Trunk muscles have also been shown to be weaker in participants after stroke than in healthy controls [51–53]. While these findings have important clinical implications, these studies did not investigate whether these trunk impair- ments also featured altered alignment.

These findings overall do provide some insight into how trunk muscle performance and upper body alignment may be altered after ABI but are insufficient to answer the question of whether better postural alignment relates to better mobility skills after ABI. As it has been shown that a stable, upright trunk is a feature of walking in healthy adults [41–43], this could represent a gap in knowledge of a key biomechanical issue after ABI. Therefore, this systematic review aimed to identify published evidence of a relationship between postural alignment and mobility for adults following ABI.

Methods

The protocol for this systematic review was registered with PROSPERO, registration number CRD42015019867, and the review undertaken in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [54]. Systematic database searches were completed using Embase, Scopus, MEDLINE, CINAHL, Web of Science, SPORTDiscus and Cochrane (Cochrane Central Register of Controlled Trials, Cochrane Database of Systematic Reviews, Database of Abstracts of Reviews of Effects, Health Technology Assessment Database, Economic Evaluation Database) in May 2015. Grey literature was searched using ProQuest Thesis and Google Scholar. No limitations were set for publication date or language.

The search strategy had strings related to brain injury, postural alignment and mobility. Three researchers designed the search strategies, with input from an academic librarian. MeSH terms (Medical Subject Headings) were reviewed for developing the search strings, with multiple search terms used to achieve as complete a search output as possible. The search strategy was adapted for the requirements of each database, with the MEDLINE search strategy shown in Figure 1. Google Scholar used an abbreviated search string due to the very high number of hits (Figure 1). Where the database allowed, the search was limited to adults and humans.

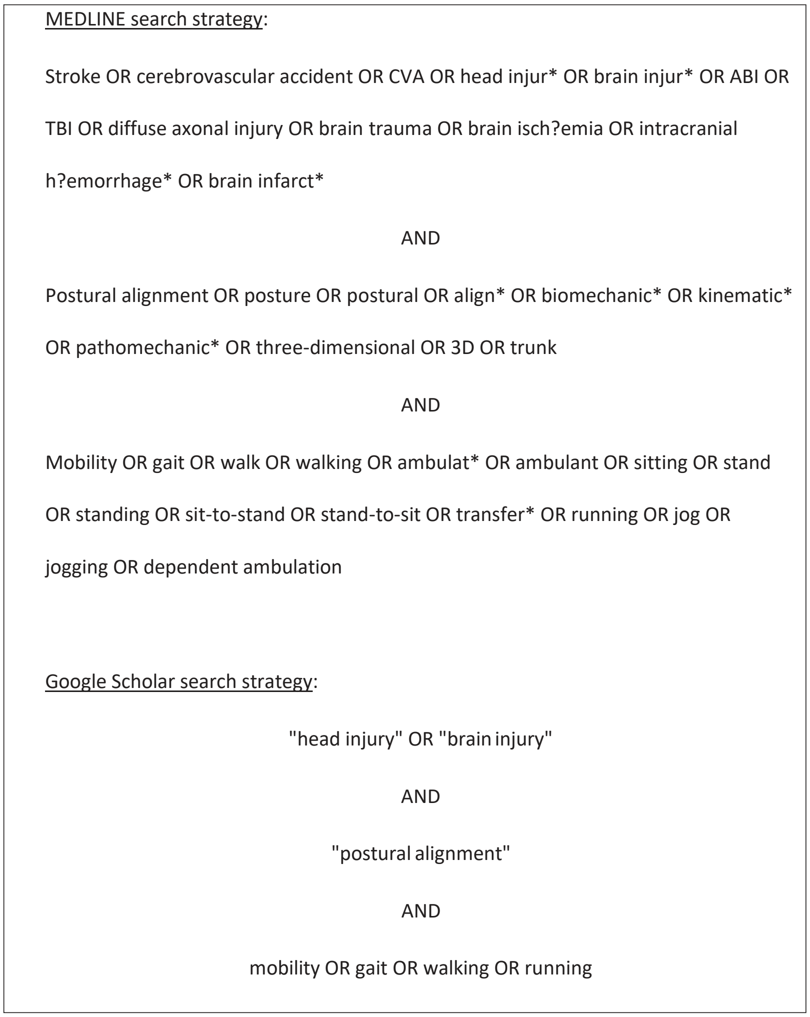
Initial search output was screened by one researcher (SJM) for potentially eligible records. Full-text studies were reviewed by two researchers. Inclusion required both researchers to agree on a study being eligible; if consensus was not reached a third researcher was consulted. Studies were included if they were empirical studies with participants who were adults with ABI, included measures of both postural alignment and mobility, and their analyses included a relationship between alignment and mobility. In the event that studies reported collecting postural alignment and mobility data, but reported no analysis of a relationship, authors were contacted to obtain data for calculating this relationship. Postural alignment was defined as the alignment of body segments relative to vertical when upright [55], which for this review needed to include head or thorax. Assessing the position of the thorax using acromion markers was an accepted method. Measurement of the upper body needed to occur directly from the body segments, not extrapolated from force plate data. Mobility was defined as any element of moving from place to place, including sit-to-stand, standing, walking and running. Any type of study design was considered, as it was recognised that the number of publications on this topic was likely to be relatively low and observational studies were most likely to report the variables required. Abstract-only publications were excluded. Included articles were critically appraised independently by two researchers using the Critical Appraisal Skills Programme (CASP) cohort study checklist (casp-uk.net), with questions about exposure and follow-up omitted as these were not relevant to this review, creating a score out of 11. Data extraction was performed by each researcher using a customised spreadsheet.

Results

Total search output prior to searching Google Scholar was 10 657 titles; duplicates were removed using Endnote software leaving 6469 titles. Duplicate titles from Google Scholar were not removed due to the difficulty to export the titles into Endnote from this database, leaving 6872 titles for review (see Figure 2). 94 articles were shortlisted for full-text review. Of these, 15 studies reported at least one measure of postural alignment and at least one measure of mobility. Four of these had reported on the relationship between those measures, and one other had reported individual participant data that allowed the relationship to be calculated. Authors of the remaining 10 studies were contacted to see if data were available to allow for calculation of the relationship. Data were provided from two of these studies, and the remaining eight studies were excluded due to the lack of data regarding the relationship between postural alignment and mobility [56–63]. Reference lists of all 15 articles were checked, with no further eligible studies identified.

Assessment of studies

All seven included studies were observational; five of these included comparison with a healthy sample. CASP scores were generally high and ranged from 8/11 to 11/11. For the studies that did not score 11/11, the criteria that were not met



MEDLINE search strategy:

Stroke OR cerebrovascular accident OR CVA OR head injur* OR brain injur* OR ABI OR TBI OR diffuse axonal injury OR brain trauma OR brain isch?emia OR intracranial h?emorrhage* OR brain infarct*

AND

Postural alignment OR posture OR postural OR align* OR biomechanic* OR kinematic* OR pathomechanic* OR three-dimensional OR 3D OR trunk

AND

Mobility OR gait OR walk OR walking OR ambulat* OR ambulant OR sitting OR stand OR standing OR sit-to-stand OR stand-to-sit OR transfer* OR running OR jog OR jogging OR dependent ambulation

Google Scholar search strategy:

"head injury" OR "brain injury"

AND

"postural alignment"

AND

mobility OR gait OR walking OR running

Figure 1. Database search strategies.

were method of sampling (used convenience sampling, or not stated), and identification/management of confounding factors. Following appraisal of the studies, all were confirmed for inclusion in the final review. It was noteworthy that none of the studies' primary aim was to investigate the relationship between postural alignment and mobility. Most studies col- lected and analysed a range of data; only the data relating to this systematic review's question are reported here.

Participant characteristics

A summary of the included studies is presented in Table I, with participant characteristics for each study. Five of the studies investigated people with stroke, and two investigated people with TBI. Reported age ranges in the participants with stroke were 37–78. Age in the participants with TBI ranged from 17 to 54. The studies including 17-year-old participants were included in this review, as the participants were recruited from an adult rehabilitation service. The samples of participants with stroke had approximately twice as many males as females, whereas the combined samples of participants with TBI had 78% males. All studies of participants with stroke reported participants to be in the chronic phase after stroke, with many participants several years post-stroke. The participants with TBI ranged from 38 days to several years post-injury.

Assessment of postural alignment

Postural alignment measures are shown in Table I. Of the seven studies, six used retroreflective markers in a Biomechanics Laboratory to assess alignment of the trunk during walking; none reported head alignment. Location of markers to calculate trunk position varied between studies, with C7, T2, T10, bilateral acromions and sternum all used. The studies varied in which aspects of trunk alignment were analysed. Two studies examined flexion and lateral flexion of the trunk during walking or running [25,45], using markers on T2, T10 and sternal notch. Two studied lateral displace- ment of the trunk during treadmill walking [64,65], measured as distance of C7 marker lateral displacement, rather than as angle of trunk lateral flexion. One study examined trunk flexion and rotation during overground walking, using acro- mion and Anterior Superior Iliac Spine (ASIS) markers [66]. One study examined thoracic rotation during treadmill walk- ing, using bilateral acromion and midsternum markers [67]. The remaining stroke study used a Spinal Mouse [46], which

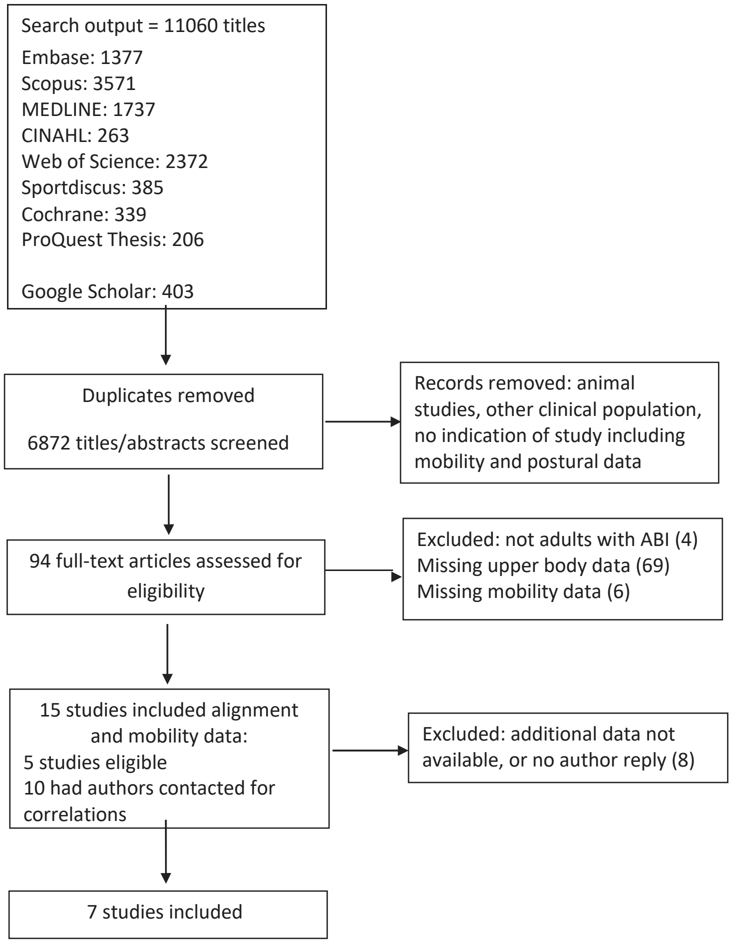


Figure 2. Flow diagram of search process.

is a mechanical device rolled over the paravertebral region between C7 and S3 vertebrae, to gauge seated and standing vertebral alignment in flexion/extension.

Assessment of mobility

Mobility measures are also shown in Table I. Three of the studies of participants with stroke used treadmill walking to assess walking speed [64,65,67]. Other mobility measures used in these studies included the Timed Up and Go, timed stairs, Functional Gait Assessment, and BESTest 6. One study of participants with stroke used step length and stride length with and without a walker as the only measure of mobility [66]. The remaining study of participants with stroke did not use a specific mobility score, it used the Barthel Index which includes 3 items of mobility (ambulation, stairs and transfers) in its 10 items, and Berg Balance Scale [46]. The studies of participants with TBI used the High Level Mobility Assessment Tool (HiMAT), and walking and running velocities [25,45].

Relationship between alignment and mobility

These results are summarised, and correlation values provided, in Table I. De Bujanda et al. [65] evaluated lateral trunk displacement during treadmill walking after stroke, and reported that better scores on the four mobility tests were significantly correlated with lesser lateral trunk displacement. De Bujanda et al. [64], appearing to use the same sample as the previous study, reported that the relationship between lesser lateral trunk displacement and faster natural walking speed on a treadmill was not statistically significant. In the study by Egan [66], the two correlations that achieved statistical significance were trunk rotation correlating with step length with walker and with left stride length with walker. None of the correlations were statistically significant when walking without a walker. The study by Hacmon et al. [67] of treadmill walking in people after stroke reported that greater thoracic rotation during treadmill walking correlated with lower scores on Functional Gait Assessment and BESTest 6, with these relationships statistically significant. Verheyden et al. [46] reported that forward inclination of the trunk during standing tended to correlate with lower scores on clinical measures. Negative correlation between trunk flexion and Berg Balance score was statistically significant, whereas the relationship did not achieve significance for Barthel Index. Correlations between sitting posture and mobility measures were much lower and were not statistically significant. Williams et al. [45] reported significant correlations between both walking speed and HiMAT score with trunk lateral flexion after

Table I. Overview of studies included in review.

Study	Participants	Age	Alignment measures	Mobility measures	Correlation coefficients (statistically significant r values shown in bold)	CASP Declaration of funding
De Bujanda 2003 [65]	Chronic stroke, n = 10 1 female, 9 male Mean time since stroke 69 (±26) months	Mean age 57.7; range 37 - 65	C7 mean lateral displacement during treadmill walk (2D)	Natural walking speed on treadmill Maximal walking speed on treadmill Stairs per minute Timed Up & Go	*C7 lateral displacement (nat speed)* / *C7 lateral displacement (max speed)* *TUG* **0.68*** **0.71*** *Climbing stairs* **−0.72*** **−0.77*** *Nat Walk Speed* **−0.79*** **−0.75*** *Max Walk Speed* **−0.75*** **−0.66***	9/11 Researchers supported by a scholarship from FRSQ and salary support from CIHR.
De Bujanda 2004 [64]	Chronic stroke, n = 10 1 female, 9 male Mean time since stroke 69 (±26) months	Mean age 57.7, range 37 - 65	C7 mean lateral displacement during treadmill walk (2D)	Natural walking speed on treadmill	C7 displacement & Natural walking speed: r = −0.52	11/11 Financial support from FRSQ and CIHR.
Egan 2015 [66]	Stroke n=5 1 female, 3 male, 1 not stated Time since stroke stated only as subacute	Age range 43-78	Trunk flexion, trunk rotation during overground walking with and without walker: markers on acromions and ASIS	Step length and stride length during walking, with and without walker	*Trunk rot with* / *Trunk rot without* / *Trunk flexion with* / *Trunk flexion without* *Step length with walker* **−.90*** .40 *Step length without* −.70 −.50 *R stride length with walker* −.50 .50 *R stride length without* −.70 −.50 *L stride length with walker* **−.90*** .40 *L stride length without* −.70 −.50	8/11 No statement of funding
Hacmon 2012 [67]	Chronic stroke n=11 3 female, 8 male Mean time since stroke 32 (±26) months	Mean age 62 years (±11)	Range of thoracic rotation during one stride of treadmill walk: markers on acromions and midsternum	Functional Gait Assessment BesTest 6 (Gait Stability)	Thoracic rotation & FGA: **r = −0.54** * Thoracic rotation & BesTest 6: **r = −0.63** *	10/11 Study partially supported by the CIHR. Researcher supported by HSFC and the Physiotherapy Foundation of Canada.
Verheyden 2014 [46]	Chronic stroke n=21 9 female, 12 male Mean time since stroke 7 years (±6.6)	Age 67 (±10)	Trunk inclination using SpinalMouse in comfortable upright posture	Berg Balance Scale Barthel Index	Standing trunk inclination & BBS: **r = −0.64*** Standing trunk inclination & BI: r = −0.51 Seated trunk inclination & BBS: r = −0.15 Seated trunk inclination & BI: r = 0.10	10/11 The authors declare no source of funding.
Williams 2009 [45]	TBI n=41 11 female, 30 male n=28 of these included alignment data	Mean age 29.1 years, range 17−54	Mean trunk flexion, mean trunk lateral flexion during overground walking: markers on T2, T10, sternal notch	HiMAT Self-selected walking velocity	*Trunk flexion* / *Trunk lateral flexion* *Walking velocity* 0.365 **0.49**** *HiMAT* 0.271 **0.39***	10/11 Supported by the Victorian Neurotrauma Initiative and RACV.

Williams 2013 [25]	TBI n=44 8 female, 36 male	Age range 17−54	Mean trunk flexion, mean trunk lateral flexion during overground running: markers on T2, T10, sternal notch	HiMAT Self-selected running velocity		*Trunk flexion*	*Trunk lateral flexion*	8/11 Supported by a fellowship from the Victorian Neurotrauma Initiative
					Running velocity	−0.001	0.021	
					HiMAT	0.255	0.173	

*p < 0.05; **p < 0.0.1

2D, two dimensional (±) = standard deviation; FGA = Functional Gait Assessment ASIS, anterior superior iliac spine; HiMAT, high level mobility assessment tool; TBI, traumatic brain injury; FRSQ, Fonds de la recherche en sante´ du Que´bec; CIHR, Canadian Institute of Health Research; HSFC, Heart and Stroke Foundation of Canada; RACV, Royal Automobile Club Victoria.

TBI. Correlations between these mobility scores and trunk flexion were not statistically significant. Williams et al. [25] examined running speed and HiMAT after TBI, and reported non-significant correlations between these scores and both trunk flexion and lateral flexion.

Comparing results between studies, we attempted to pool data from studies with similar methods. Although three stu- dies reported on both lateral trunk displacement and walking velocity [45,64,65], the methods used to measure postural alignment were not similar enough to combine them for meta-regression.

Discussion

Results of this systematic review indicate that the relationship between postural alignment and mobility skills after ABI is not clear. Published evidence has not established whether better postural alignment either is or is not correlated with more advanced mobility skills after ABI. The low number of eligible studies, the varied measures of mobility and postural alignment used, the lack of consistency in relationships calcu- lated in the included studies, and the generally small sample sizes provide limited insight into this relationship.

This review has also demonstrated that postural alignment is typically absent from biomechanical research on mobility after ABI. Only a tiny proportion of the mobility studies screened in this systematic review investigated any alignment of the upper body. It was noted that some studies that col- lected data on the upper body did not report it, and had not included the upper body in their planned analysis. The included studies also did not focus on postural alignment being a factor to influence mobility skills—the correlations reviewed here were often not part of the aims of the studies. Three of the included studies had not reported a correlation between their postural alignment and mobility scores; calcula- tions from provided data were made for the purpose of this systematic review.

Five of the seven studies demonstrated one or more statistically significant correlations between an alignment measure and a mobility measure (Table I). The significant correlations in the studies of participants with stroke supported a more stable, upright trunk correlating with better mobility. The trend was different in participants with TBI [45], where better mobility scores were correlated with greater trunk lateral flexion during walking. Correlations with trunk flexion were not statistically significant. Understanding the variation in these findings would be aided by greater understanding of postural alignment in healthy adults and how it differs after brain injury. The variation in measures used to evaluate alignment in the included studies may indicate that optimal methods for measurement need further determination, but also that the aspects of upper body alignment that are most significant to mobility performance are not yet understood. There were also marked differences in methods used to mea- sure mobility. Walking was the most frequently evaluated aspect of mobility in the studies included in this review. Three studies evaluated walking solely on a treadmill, which has previously been found to alter overground kinematics of walking after stroke [68,69]. In the study by Egan [66], only stride and step length were measured to represent walking performance, providing a limited rating of walking skills. This study also did not report whether trunk flexion measures were peak trunk flexion, average, or another parameter, which makes interpretation more difficult. Egan [66] reported that two of the five participants had a statistically significant decrease in trunk flexion with walker compared to walking without walker, indicating participants may have compen- sated for a lack of postural extension by propping themselves with their arms. The other three participants had no signifi- cant difference with and without the walker. Verheyden et al.

[46] did not include a pure mobility measure in their study of people with stroke, potentially limiting the application of their findings to pure mobility skills.

Evidence exists for multiple aspects of motor training to improve mobility and this is a core area for rehabilitation [70]. The search undertaken for this systematic review has demonstrated that despite a huge volume of kinematic research on mobility after brain injury, a whole-body under- standing of kinematics of mobility skills such as walking is lacking. There is a dearth of evidence relating to the upper body and postural alignment, leaving a question about whether there are similar gaps in clinical practice. The major- ity of body mass lies in the upper body; Winter [71] describes that two-thirds of body mass lies two-thirds of body height above the ground [71]. From this simple anatomical perspec- tive, the upper body appears too important to ignore in biomechanics.

Trunk muscle training has received increasing attention in recent research in neurological rehabilitation, with multiple randomised controlled trials published. Sorinola et al. [72] reported in their meta-analysis of additional trunk exercises for people after stroke that trunk exercises during sitting and lying significantly improved standing balance and mobility scores early after stroke. Cabanas-Valdes et al. [73] reported in their systematic review of trunk training in people after stroke that sitting balance scores and Trunk Impairment Scale scores tended to improve in the trunk exercise groups. None of the studies included in these reviews used a measure of postural alignment, although one used a measure that had reference to upright posture [74].

While specific motor impairments and postural alignment have each been researched after brain injury, these have not tended to be evaluated together. The study by De Bujanda et al. [65] reported that decreased lateral control of the trunk correlated with reduced walking capacity on a treadmill after stroke. This study correlated lateral trunk displacement with other variables including Chedoke-McMaster leg and foot scores but did not measure muscle performance of the trunk or pelvis, so it was not apparent what motor impairment was most related to the degree of trunk displacement. Studying sit- to-stand mechanics, Mazza et al. [75] reported that greater extension of head and torso during sit-to-stand after stroke related to improved performance. They measured muscle strength in these participants, but only of leg muscles, so it was not apparent whether trunk muscle strength was related to the mechanics of the upper body. Despite the growth in research of trunk muscle performance, it does not seem clear which motor factors most influence postural alignment.

There are a few clinical measurement tools available to rate posture in neurological populations [55], and none of the included studies used one. Use of a validated clinical tool could have allowed for meta-analysis of results, and also could assist with application of results to clinical practice. In a systematic review of tools to measure posture, it was recom- mended that a new measurement tool would need to be developed to meet requirements for clinical utility in stroke rehabilitation [55]. While there are measurement tools for walking that include posture, these were not used in any of the studies included in this review. A systematic review of observational analysis scales for assessing walking after stroke showed that four of five eligible scales included the upper body as part of global walking analysis [76]. The scales includ- ing the upper body were the Rivermead Visual Gait Assessment [77], Gait Assessment and Intervention Tool [78], Hemiplegic Gait Analysis Form [79] and New York Medical School Orthotic Gait Analysis [80], whereas the Wisconsin Gait Scale [81] does not include the upper body. While this demonstrates that options are available for clini- cians to include upper body quantitative measurement, these scales may not be commonly used. There are multiple factors that could affect the uptake of a measurement tool including the clinicians' perception of relevance and applicability, time required, precision and usefulness of the information pro- vided by the measure [82,83]. The lack of research publica- tions including upper body posture may be a factor limiting the clinical uptake of the tools that include it. The limited number of tools for clinicians to evaluate posture could also contribute to it being neglected in clinical assessment. The term 'lower limb function' is commonly used to refer to walking [84,85], which may also limit the recognition of walking as a whole-body activity.

Three-dimensional kinematic analysis of walking has been shown to be generally highly reliable in a systematic review [86], although it is illustrative that there were no upper body data reported from any of the included studies in the review. 3D kinematic analysis has been recommended over observa- tional analysis based on degree of observer accuracy [87], although like all measurement tools 3D kinematic analysis has its own strengths and limitations. A key strength is that any body segment can be included, and most studies included in the present systematic review used 3D kinematic analysis to observe and rate one or more aspects of postural alignment of the upper body. However, the facilities, skills and time required for this are not available to all clinicians, so other means of analysis and measurement are also required for clinical practice and research. Options for analysis of posture in musculoskeletal practice have been described in a systema- tic review; the methods listed were photography, goniometry, inclinometry, tape measurement, and use of a flexible device to measure spinal curves [88]. Measurement of body angles from photographs was described as likely to be the most quick and accurate method clinically. Photogrammetry has also been used for the measurement of different aspects of posture following stroke [89], so it could offer an achievable two-dimensional option.

Motor performance of the trunk has been included in the development of several measurement tools in the brain injury field. Tools rating trunk performance have commonly included items such as rolling, sitting balance and lie-to-sit [90–94]. This indicates that posture has not been consistently included in analysis of trunk performance, despite posture being a key role of trunk muscles. There is an opportunity to expand the scope of clinical assessment and clinical research to include the upper body during mobility more consistently. However, it is yet to be established how signifi- cant postural skills are relative to the skills currently included in trunk-related scales.

Many people live with marked limitations in mobility for years after surviving a brain injury [7,95]. It is important that clinicians and researchers continue to seek means of improving outcomes, and progressing evaluation and training of mobility skills is an important component. The gaps in evidence may be greater for populations with severe physical impairment after ABI [96]. Severity of physical impairment can be a factor that precludes some people from being provided with rehabilitation services after ABI [97], so for severely impaired groups the need to develop improved methods of assessment and intervention may be even more critical. It is noteworthy that each of the participant groups included in this review were independent with mobility. Biomechanical research has commonly focussed on people who are independent with walking after ABI, so less is known about the biomechanics of mobility for those who are not independently ambulant. From the included studies in this review, trunk flexion during independent running was not found to be significantly different between TBI and healthy samples [25], whereas greater trunk flexion during independent walking was observed after TBI [45]. It was hypothesised by the authors that an upright trunk may be a requirement to achieve running after TBI, which may indicate that postural skills are important for advancing mobility performance. However, this does not identify the importance of postural skills for those who need assistance to walk after ABI. A study of adults after stroke comparing the kinematics of walking with different walking aids found no difference in kinematics using the different aids. It showed that more symmetrical and stable pelvic motion corre- lated with faster walking speed, but did not include data from body segments above the pelvis, so the postural performance was unknown [37]. A novel kinematic study of adults with ABI who needed assistance to walk found clinically useful differences in walking under different training conditions, but did not report data on upper body alignment [98]. It did demonstrate that the mode of assistance influenced walking parameters, which has implications for rehabilitation professionals who train walking. While the need for more knowledge of postural alignment dur- ing mobility applies to ambulant and non-ambulant groups with ABI, there is a particular need for greater knowledge about optimising mobility outcomes for those who lack independence.

Implications

There is limited evidence that a more stable, upright trunk is associated with better walking after ABI, and other evidence that found the opposite or ambiguous results. While the review has not identified adequate evidence to demonstrate the strength of the relationship between postural alignment and mobility, there is no indication that the upper body should be excluded from analysis of mobility after ABI. There is a suggestion for clinicians that it may be worthwhile to include posture when evaluating mobility.

There is also an implication for clinical research; the upper body is relevant to consider when investigating the kinematics of mobility after ABI. There is a clear need for more research studies to gather and analyse data on the upper body during mobility. Larger studies with methods that allow for pooling of data are needed to provide more generalizable findings.

Limitations

This review identified a low number of studies relevant to the research question. Publication bias could not be statistically assessed due to having fewer than 10 included studies.

Conclusion

Evaluation of postural alignment during mobility for adults after ABI is lacking in published research. The evidence that exists is insufficient to answer the question of how much postural alignment relates to mobility after ABI.

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Declaration of Interest

The authors declare no conflict of interest, and no source of funding. The authors are solely responsible for the content and writing of the paper.

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