Gait & Posture 43 (2016) 265–269

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

The distribution of positive work and power generation amongst the lower-limb joints during walking normalises following recovery from traumatic brain injury

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ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form 28 July 2015
Accepted 13 October 2015

Keywords:
Brain injuries
Quantitative gait analysis
Mobility limitation
Inverse dynamics

ABSTRACT

Objective: To determine whether better walking performance following recovery from traumatic brain injury (TBI) is attributable to an accentuation of compensatory strategies or an improvement in the way positive work is done and power is generated by the lower-limb joints. *Setting*: A large metropolitan rehabilitation hospital. *Participants*: Thirty-five ambulant people with extremely-severe TBI who were attending physiotherapy for mobility limitations, and a comparative sample of 25 healthy controls (HC). *Design*: Cross-sectional cohort study with six month follow-up. *Main Measures*: Positive work done and average power (i.e. over time) generation by the hip, knee and ankle during stance as well as self-selected gait velocity. *Results*: In comparison to HCs, TBI participants walked at baseline with a significantly ($p < .01$) reduced contribution from the ankle to total lower-limb average power generation (and positive work done) during stance, and a significantly ($p = .03$) greater contribution from the hip. However, this compensatory strategy resolved over time such that at six month follow-up no significant differences in the relative contributions from the ankle and hip were identified for the TBI participants when compared to HCs. *Conclusion*: Better walking performance following recovery from TBI is attributable to an improvement in the way positive work is done and power is generated by the lower-limb joints rather than an accentuation of compensatory strategies.

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1. Introduction

People who have suffered a very severe traumatic brain injury (TBI) often make significant recovery in their mobility [1]. Gait disorders following TBI may be disparate [2], and a wide range of physical impairments can potentially contribute to mobility limitations [3]. Slow walking was originally thought to be related to poor balance and postural instability [4]. However, Williams et al. [3] demonstrated that despite residual problems with postural instability people with TBI walked slowly due to reduced ankle power generation (i.e. the rate at which positive work is done by the ankle) during late stance, and this deficiency was compensated for by greater hip power generation. Furthermore, large improvements in balance following rehabilitation were not found by Williams et al. [5] to be related to faster walking speeds. Ankle power generation during late stance and improved motor control together predicted 66.5% of the variability in mobility outcome [5], suggesting that these two factors are likely to be highly influential on the ability to attain faster walking speeds following TBI.

In healthy able-bodied walking, there are three main muscle groups that are responsible for generating most of the power required by the lower-limb for forward propulsion. These muscles groups are the hip extensors during early stance as well as the hip flexors and ankle plantar-flexors during late stance [6–8]. Lower-limb power generation during walking in people with TBI has not been thoroughly investigated; however, current evidence suggests that slower walking speed and mobility limitations following TBI are associated with reduced ankle power generation during late stance [5]. Reduced ankle power generation during late stance is compensated for by increased hip extensor and flexor power generation during early and late stance, respectively [3]. This intra-limb compensatory pattern is accentuated when people with TBI walk at faster speeds [3].

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http://dx.doi.org/10.1016/j.gaitpost.2015.10.009
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Better walking performance can be expected to occur over time for the majority of people with TBI; however, the underlying factors behind this improvement remain unclear. Two basic strategies are possible. Firstly, people may learn to compensate for their neurological impairments more effectively and efficiently, thereby accentuating this proximal compensatory pattern. Alternatively, people may improve their ankle power generation as they recover, negating the need to execute a proximal compensatory pattern. However, the extent to which the distribution of power generation amongst the lower-limb joints is restored in people with TBI following rehabilitation remains unknown.

The aim of this study was to determine whether better walking performance following TBI is attributable to an accentuation of compensatory strategies or an improvement in the way positive work is done and power is generated by the lower-limb joints.

2. Methods

A cohort study and sample of convenience was used.

2.1. Participants

Participants with TBI currently attending physiotherapy for gait limitations at Epworth Healthcare, Melbourne, Australia were voluntarily recruited. The research project was approved by Epworth Hospital's Human Research and Ethics Committee (study number 34006) and by The University of Melbourne (Ethics ID: 060496.1). The inclusion criteria were participants who: (a) had sustained a TBI and; (b) were able to walk independently over a distance of 20 m without the use of a gait aid. Exclusion criteria were participants who: (a) were unwilling or unable to provide informed consent; (b) presented with concurrent central nervous system disorders and; (c) had severe cognitive or behavioural problems that prevented assessment. Data were also collected from a sample of 25 healthy control (HC) participants. The HCs had no central nervous system disorders or previous musculoskeletal injury that adversely impacted on their walking ability.

2.2. Procedures

Experimental data of interest were collected while participants walked over a 12 m distance in the laboratory at The University of Melbourne. Participants with TBI walked at their self-selected speed. In order to ensure consistency in walking speed across the two cohorts, HCs were asked to walk at a speed comparable to the mean (±5%) TBI self-selected walking speed (averaged across the baseline and six-month follow-up data). Healthy controls were given verbal feedback regarding the accuracy of the matched speed. Only trials within 5% of the mean TBI self-selected walking speed were included. Five trials of data were recorded for all participants. Participants with TBI nominated their more affected leg for analysis, whereas the right leg was used as the representative leg for the HCs.

Twenty-five (14 mm diameter) reflective markers were mounted on the skin at specific locations on the pelvis and both lower limbs following a previously described protocol [9]. Participants initially performed a standing anatomical calibration trial, with additional markers placed on the medial femoral condyle, medial malleolus and proximal posterior calcaneum of both legs. These markers were used to define joint centre locations and anatomical coordinate systems [9]. The location of the hip joint centre was predicted using the method of Harrington et al. [10]. Pelvis and lower-limb marker trajectories were recorded using a motion analysis system (Vicon 512, Vicon Motion Systems Ltd. UK) with eight cameras sampling at a rate of 120 Hz. Ground reaction force data were collected using three ground-embedded force plates (Advanced Mechanical Technology Inc., Watertown, MA, USA) sampling at a rate of 1080 Hz.

2.3. Rehabilitation program

Participants with TBI were receiving rehabilitation for gait and mobility limitations. The types of exercises typically performed in the rehabilitation program have been described previously [11–13]. Briefly, the rehabilitation program focused on task-specific or ballistic strength training in order to optimise muscle function for walking. Patients received 1–2 centre-based therapy sessions per week, and performed either a home-based or gym-based program 3–4 times per week. The home or gym-based programs were developed by the centre-based staff and were regularly reviewed and progressed accordingly. Although a prerequisite level of leg strength is required in all muscle groups for walking, recent findings in TBI and stroke indicate that it is ankle power generation for push-off that needs to be preferentially treated [5,14]. Therefore, a key focus with the majority of the exercises was to improve the rate of force production.

2.4. Data analysis

For each participant, data for all five recorded trials were visually inspected and a representative trial was selected for analysis. Three-dimensional lower-limb joint kinematic and kinetic calculations were performed using Bodybuilder software (Vicon Motion Systems Ltd. UK). Our seven-segment biomechanical model has been described in detail elsewhere [9].

The process for calculating lower-limb joint work and average power was as follows. First, a standard inverse dynamics approach was used to compute lower-limb joint moments [15]. Second, for each lower-limb joint, the net power across all three planes was determined by calculating the product of the net joint moment and joint angular velocity. For each participant, the net joint power data were normalised to body mass (W/kg). Third, the normalised net joint power data were integrated over the duration of the stance phase to determine the work done (J/kg). All periods of positive work were summed independently to determine the total amount of positive work done by each joint. Fourth, the total amount of positive work done by each joint was divided by the stance time to determine the average power generated by each joint. The average power generated by each joint (hip, knee and ankle) was summed to determine the total average power generated by the lower-limb throughout stance. The average power generated by each joint was then expressed as a percentage of the total average power generated by the lower-limb. Note that these percentage contributions are equivalent to those obtained by expressing the positive work done by each joint as a percentage of the total positive work done by the lower-limb.

Summary statistics (mean and standard deviation) were generated for all variables of interest. Comparisons between the TBI and HC cohorts were made using an independent two-tailed *t*-test. Paired *t*-tests were used to determine whether variables of interest for the TBI participants changed over a six-month period. Finally, given the potential for biomechanical parameters to be influenced by walking speed, we used hierarchical multiple regression [16] to determine whether the change over time in the proportional contribution from the hip to total lower-limb average power generation for the TBI participants was related to change over time in the proportional contribution from the ankle, controlling for the effect of differences in walking speed. The change in walking speed was entered first, followed by the change in the proportional contribution from the ankle. All data analyses were completed using the IBM SPSS Statistics package (v21). Statistical significance was set a priori at $p < 0.05$ for all tests.

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