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Assessment of standing balance deficits in people who have undergone anterior cruciate ligament reconstruction using traditional and modern analysis methods

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ABSTRACT

Modern methods of assessing standing balance such as wavelet and entropy analysis could provide insight into postural control mechanisms in clinical populations. The aim of this study was to examine what effect anterior cruciate ligament reconstruction (ACLR) has on traditional and modern measures of balance. Ninety subjects, 45 who had undergone ACLR and 45 matched controls, performed single leg static standing balance tests on their surgical or matched limb on a Nintendo Wii Balance Board. Data were analysed in the anterior–posterior axis of movement, which is known to be affected by ACLR. The traditional measures of path velocity, amplitude and standard deviation were calculated in this plane. Additionally, sample entropy and discrete wavelet transform derived assessment of path velocity in four distinct frequency bands related to (1) spinal reflexive loops and muscle activity, (2) cerebellar, (3) vestibular, and (4) visual mechanisms of postural control were derived. The ACLR group had significantly increased values in all traditional measures and all four frequency bands. No significant difference was observed for sample entropy. This indicated that whilst postural sway was amplified in the ACLR group, the overall mechanism used by the patient group to maintain balance was similar to that of the control group. In conclusion, modern methods of signal analysis may provide additional insight into standing balance mechanisms in clinical populations. Future research is required to determine if these results provide important and unique information which is of benefit to clinicians.

1. Introduction

A number of computerised posturography studies have shown balance deficits in people who have undergone an anterior cruciate ligament reconstruction (ACLR), including both inter-limb differences and reduced performance relative to a healthy control population (Bonfim et al., 2003; Henriksson et al., 2001; Hoffman et al., 1999; Howells et al., 2011). These studies have focused on traditional measures of balance assessment commonly derived from force plates such as centre of pressure (COP) path length, velocity, amplitude, root mean square and area. While these measures have proven adept at identifying balance deficits in this population, they do not necessarily provide insights into the nature and mechanisms of the balance impairment. For example, it is possible to achieve the same path length and velocity score using different strategies—one person may have a relatively stable position interspersed with rapid oscillating, small amplitude movements while another person may have a consistent pattern of less-rapidly oscillating, but larger amplitude movements. Despite achieving the same balance score outcome, these two strategies likely reflect disparate postural control strategies, with the former representing an open-loop strategy heavily reliant on feedback from the muscle spindles and other proprioceptive organs and the latter reflecting a closed-loop system that is predominantly controlled by the visual and vestibular systems (Kirchner et al., 2012).

As a consequence, attempts have been made to independently analyse the components of standing balance from COP traces using methods such as multi-scale wavelet analysis (Kirchner et al., 2012; Treleaven et al., 2005). This separates the signal into different components based on their frequency content, with the relatively

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rapid fluctuations associated with high frequency movement and the slower fluctuations associated with low frequency movement converted into independent signals for separate analysis. This technique allows for the evaluation of not just whether balance deficits exist, but the movement strategies which underpin the impairment.

Assessing signal irregularity using techniques such as entropy analysis has been previously referred to as a method of assessing the health of the neurological system (Borg and Laxaback, 2010; Ramdani et al., 2009; Rhea et al., 2011). Reference has been made to greater regularity in the balance signal compared to a healthy population representing a postural control system which is less able to react efficiently to an unexpected perturbation, and hence increased irregularity in the signal is deemed beneficial (Borg and Laxaback, 2010). However, conflicting views highlight that increased irregularity may be reflective of a control system which is not effectively integrating the different systems and is becoming more chaotic (Borg and Laxaback, 2010). The only study to use irregularity analysis in an ACL population observed that people who were ACL deficient had a more regular COP pattern in their injured leg compared to a healthy cohort (Negahban et al., 2010).

A small but growing number of studies have used wavelet based analysis to identify components of balance, mostly in healthy populations. Similarly, there is limited research using irregularity analysis in posturography, and it remains unclear how this variable is affected by different clinical conditions. However, there may be great potential for these techniques to be used in unison for assessment of balance data collected in clinical populations with known balance impairments, such as those who have undergone lower limb surgery, because the information obtained from these measures could be used to guide rehabilitation programs. Therefore, the aim of this study is to assess balance using traditional, wavelet and signal irregularity based measures in a group of ACLR and matched control subjects.

2. Methods

The results reported in this paper are derived using new analysis techniques performed on the data collected in a previous study (Howells et al., 2013). Consequently, the participants and data collection methods are identical to this previously published work, and will be summarized in the following sections. Two groups of 45 participants (15 females in each) were recruited into this study, one consisting of people who had undergone an uncomplicated primary ACLR with a four strand hamstring autograft and the other a matched control group. Sample size was estimated based on a moderate effect size, as reported by a previous study in ACLR with a similar design (Alonso et al., 2009), resulting in a minimum sample size of 68 participants (34 per group with $\beta=0.2$, $\alpha=0.05$). Ethics approval was obtained from the Faculty Human Ethics Committee and all participants provided written consent prior to participation.

2.1. Anterior cruciate ligament reconstruction group

Participants were 6–18 months post-surgery and were recruited from the private practices of two experienced knee surgeons during their scheduled 6 or 12 month follow-up assessment. Exclusion criteria were; (1) previous or concurrent posterior or collateral cruciate ligament injury, (2) history of visual, vestibular or neurological disorders, (3) use of ototoxic medications (e.g. chemotherapeutic agents such as methotrexate) likely to influence the postural control system within the previous six months, (4) greater than two years between ACL injury and ACLR, (5) history of lower limb, neck or back injury in the previous six weeks significantly affecting activity.

All participants underwent an arthroscopically assisted ACLR with discharge from hospital on the first postoperative day. Every patient undertook a post-operative rehabilitation protocol that encouraged immediate full knee extension and the restoration of quadriceps function as soon as possible, with particular emphasis placed on the restoration of vastus medialis function. Weight bearing was allowed on an as tolerated basis from the first postoperative day, and no braces or splints were used. Most patients were full weight bearing by 2 to 3 weeks, riding a stationary bicycle by 4 weeks and running by 3 to 4 months. Sports-specific drills were introduced from the 4 month time point.

2.2. Control group

The control group consisted of university staff and students recruited via advertisement, and recreational athletes recruited via sporting clubs. Control participants had no history of ACL injury or surgery, and no lower limb injury within the previous six months that required surgery or restricted participation in activities of daily living for greater than two weeks. Other exclusion criteria were the same as for the ACLR group. Each ACLR participant was individually matched with a control participant by age (± 4 years), gender, Cincinnati Sports Activity Scale (CSAS) physical activity level (Noyes et al., 1989) and limb dominance.

2.3. Procedure

Participants stood in a standardized position on a Wii Balance Board (WBB) (Nintendo, Japan) for testing of all postural control outcomes. The WBB has good to excellent test re-test reliability and concurrent validity compared to a laboratory-grade force platform when tested independently (Clark et al., 2010) or synchronously (Huurnink et al., 2013). The WBB was placed on a hard surface and calibrated by placing known weights on different positions on the surface of the board. The WBB was connected to a laptop computer via a Bluetooth connection and interfaced using custom LabVIEW software (National Instruments, Austin, TX, USA).

Participants stood bare-footed on the WBB on one leg, with the middle of the longitudinal axis of their foot aligned with a line showing the centre of the WBB in the AP plane. They were instructed to stand as still as possible for 30 s on their ACLR limb or matched limb for the control group. Specific positioning regarding the weight bearing knee (slightly flexed to approximately 20°), non-weight bearing knee (flexed to 90°), non-weight bearing hip (neutral flexion/extension) and hands (on hips) was adjusted on the basis of visual observation by the investigator. Participants fixed their gaze on a white dot displayed on a computer monitor positioned at eye-level 1.4 m from the WBB. Three trials of each test were performed, with a 30 s rest between trials, to minimize effects of fatigue (Salavatii et al., 2007). Trials were excluded if the participant failed to remain upright for the trial duration or had to touch their non-testing limb foot on the ground to maintain balance.

2.4. Data analysis

The data recorded from the WBB were interpolated to 100 Hz before being filtered using an undecimated wavelet-based filter (Symlet-8) with a low pass frequency of 6.25 Hz to remove noise. Specifically, a 3-level discrete wavelet transform cascade filter bank was implemented, and only the approximation level was retained. This form of wavelet filter was chosen for a number of efficacy reasons, such as improved noise reduction in kinematic data when compared to commonly implemented finite impulse response filters (Ismail and Asfour, 1999), and its compatibility with the wavelet-based data analysis that is a core component of this study.

The outcome measures derived in this study consisted of traditional and modern measures of balance derived in the anterior–posterior plane. Analysis of this plane only was performed because a previous study has reported that it is affected more than the medial–lateral plane in this population (Howells et al., 2013), and performing the same analysis on both planes effectively doubles the number of statistical evaluations and hence increases the risk of committing a type one error.

The traditional measures included:

(a) COP path velocity, which is simply the length of the AP trace divided by the duration of the trial.
(b) COP amplitude, which is the distance between the most anterior and posterior positions reached during the trial.
(c) COP standard deviation (SD), which is the SD of the COP trace in this plane, with a smaller value reflecting a more condensed trace and therefore less exploration.

The modern measures included:

a) Discrete wavelet transform based analysis of the COP trace, which consists of separating the signal into multiple independent signals based on frequency content. In this study we chose to split the signal into four bands, namely (1) moderate (1.56–6.25 Hz), (2) low (0.39–1.56 Hz), (3) very low (0.10–0.39 Hz), and (4) ultralow (<0.10 Hz) frequency. These frequency ranges were chosen because they are believed to capture postural movements associated with the spinal reflexive loops and muscle activity (Golomer et al., 1999; Paillard et al., 2002), cerebellar (Kapoula et al., 2011; Paillard et al., 2002), vestibular (Oppenheim et al., 1999), and visual systems (Chagdes et al., 2009; Friedrich et al., 2008; Patel et al., 2011), respectively. The signal bandwidths were separated using a 9-level Symlet-8 wavelet, with multiresolution analysis used to (a) combine the 4th and 5th detail levels to obtain the moderate frequency data; (b) combine the 6th and 7th detail levels to obtain the