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Coordination stability between the legs is reduced after anterior cruciate ligament reconstruction☆

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ABSTRACT

Background: The study was designed to examine coordination differences in walking between individuals with an anterior cruciate ligament reconstruction compared with healthy matched controls. Predictions from the extended Haken, Kelso, and Bunz coupled oscillator model were tested in these populations.
Methods: Seventeen persons with anterior cruciate ligament reconstruction and 17 matched controls participated in the study. Sagittal plane angular knee displacement was recorded using electrogoniometers over the lateral right and left knee joints while participants walked at five walking speeds overground. Coordination pattern and stability between the knees were quantified by mean and standard deviation of relative phase, respectively.
Findings: Mean relative phase was not influenced by walking speed or group. For both groups, coordination stability was maximal when individual's walked at their preferred gait speed. However, the anterior cruciate ligament reconstruction group demonstrated reduced coordination stability compared with healthy controls across the five speeds. Multiple regression analyses found that people with anterior cruciate ligament reconstruction who deviated more from antiphase coordination had decreased coordination stability.
Interpretation: Anterior cruciate ligament reconstruction results in decreased coordination stability, indicative of reduced coupling strength between the legs. This change in gait coordination, which has not previously been found in the literature, may contribute to the increased rate of re-injury and degeneration in individuals who have had this reconstructive surgery. Application of a motor control model enhances our understanding of the influence of an injury on coordination during gait.

1. Introduction

The primary role of the anterior cruciate ligament (ACL) is to stabilize the knee joint during locomotion. When torn, ACL reconstruction (ACLR) is often recommended to restore stability of the knee. Some of the major draw-backs of this surgery are an increased rate of re-injury to the ACL or to the ACL of the contralateral limb, and the exponential rate at which post-traumatic osteoarthritis (OA) occurs in these individuals (Lohmander et al., 2007). Early onset of OA post-ACLR has been considered to be strongly attributed to abnormal gait (Andriacchi et al., 2009), although measures of strength and walking kinematics in people with ACLR exhibit similar patterns one year post-reconstruction as healthy controls (Gao and Zheng, 2010; Karimi et al., 2013; Kaur et al., 2016). However, more than a year after surgery, alterations in knee and hip joint moments during walking have been observed in people with ACLR (Butler et al., 2009; Kaur et al., 2016; Noehren et al., 2013). It appears that standard kinematic and spatiotemporal parameters are not sensitive enough to detect modifications. Instead, measures that quantify coordination between body parts (e.g., joints or segments) may be better able to identify differences between healthy controls and individuals with ACLR that contribute to changes in kinetics (Kurz et al., 2005).

Gait coordination of individuals with chronic pain or injury has been found to differ from healthy individuals (Drewes et al., 2009; Hamill et al., 1999; Hamill et al., 2012; Heiderscheit et al., 2002; Herb et al., 2014; Miller et al., 2008; Yen et al., 2017). Studies of

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Abbreviations: ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; OA, osteoarthritis; HKB, Haken, Kelso, and Bunz; ω, stride frequency; SDϕ, standard deviation of relative phase; ω_{CV}, coefficient of variation of stride frequency; ϕ, relative phase between two oscillators; $\dot{\phi}$, derivative of relative phase; $|\phi|$, mean absolute relative phase; $\Delta\omega$, asymmetry between two oscillators (arithmetic difference in their resonant frequencies); $\sqrt{Q}\xi_t$, noise

☆ Conflicts of interest: None.

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patellofemoral pain, iliotibial band syndrome and chronic ankle instability have all revealed changes in the pattern of coordination between segments or joints of the involved limb as well as reduced coordination variability (Drewes et al., 2009; Heiderscheit et al., 2002; Herb et al., 2014; Miller et al., 2008; Yen et al., 2017). These findings of increased coordination stability of joints within a limb have been interpreted as people with injuries developing an altered and more constrained gait pattern in an effort to reduce pain while walking or running (Miller et al., 2008). While an individual with ACLR is expected to have a stable knee joint without any pain after rehabilitation, changes in coordination between segments of the involved leg have been observed, but no significant difference was observed in coordination variability compared with healthy controls (Kurz et al., 2005). With only a single study on coordination in ACLR gait there is a need for more research. There are also a number of limitations in these studies that should be considered. Firstly, these studies examined coordination within the involved limb and not between limbs. Secondly, gait was performed on a treadmill which we have previously shown can obscure coordination variability effects present in overground walking (Russell et al., 2010; Russell et al., 2016). Thirdly, by only considering one speed these studies did not provide an assessment of the changes in coordination across speeds/frequencies. And finally, the studies were not grounded in a model of rhythmic coordination that has been extensively investigated and supported by research on healthy individuals.

The extended Haken, Kelso and Bunz (HKB) coupled oscillator model has driven much of the research in human coordination of movements by providing specific testable hypotheses which have been empirically verified (Haken et al., 1985; Kelso et al., 1990). According to this model, rhythmic motion of a joint can be considered as an oscillator which is coupled with the rhythmic oscillations of another joint. The following equation can be derived from the model to make predictions about coordination between joints (Haken et al., 1985; Kelso et al., 1990):

$$\dot{\phi} = \Delta\omega - a\,\sin\phi - 2b\sin 2\phi + \sqrt{Q}\,\xi_t,$$

where ϕ is relative phase between two oscillators, $\Delta\omega$ is the asymmetry (arithmetic difference in the resonant frequency of each oscillator), b/a represents the strength of the coupling between the oscillators, $\sqrt{Q}\,\xi_t$ represents noise, and $\dot{\phi}$ is the derivative of ϕ with respect to time. This model makes several predictions that have been supported experimentally (Amazeen et al., 1995; Amazeen et al., 1996; Amazeen et al., 1998; Sternad et al., 1992; Sternad et al., 1995; Sternad et al., 1996). For present purposes we highlight four hypotheses relevant to the current study that have been previously validated in walking. Firstly, oscillators will tend to coordinate either inphase or antiphase ($\phi = 0$ or 180°, respectively). In human walking the legs move together in an antiphase fashion, while contralateral arm and leg move together in an inphase coordination pattern. Secondly, stability of the coordination (quantified inversely by the standard deviation of ϕ, SDϕ) increases as coupling strength (b/a) increases. Previously we have shown that coupling strength decreases (SDϕ increases) when moving at stride frequencies/speeds faster or slower than preferred (Russell and Haworth, 2014b). Thirdly, when the limbs are asymmetrical (i.e., differ in their preferred movement frequency) the faster limb phase leads the slower limb (ϕ deviates from 0 or 180°). Finally, the larger the asymmetry between the limbs the less stable the coordination (i.e., SDϕ will increase). These later two hypotheses have been supported when asymmetries have been created between the legs, in healthy individuals, using ankle weights (Russell et al., 2010; Russell et al., 2016).

According to the HKB-model, ACLR could influence coordination between the knees by creating an asymmetry ($\Delta\omega \neq 0$) or altering the coupling (b/a) between the legs. These two possibilities lead to different specific predictions. If ACLR changes the preferred movement frequency of the involved leg an asymmetry with the uninvolved leg would arise ($\Delta\omega \neq 0$), leading to the following predictions for the ACLR group: (1) preferred stride frequency differs from healthy controls, (2) greater deviation in relative phase from 180°, (3) greater coordination variability (SDϕ) especially at slower or faster than preferred speeds (i.e., SDϕ is a quadratic function of gait speed with greater quadratic and constant coefficients). Alternatively, ACLR may reduce the strength of the coupling (b/a) between the legs in which case (1) and (2) would not be observed, but (4) greater coordination variability would occur (i.e., SDϕ is a quadratic function of gait speed with greater constant coefficient). These predictions were assessed in the current study by quantifying coordination between the knees while participants walked overground at five different speeds relative to their preferred speed. Additionally, to determine if individual differences in asymmetry or walking speed impacted coordination stability, multiple regression analyses were performed.

2. Methods

2.1. Participants

Thirty-four individuals were recruited for the study, which was approved by the local institutional review board and conforms to the Helsinki Declaration. Seventeen of the participants had unilateral ACL reconstruction ($\bar{x}$ age: 23.5 (SD: 2.73) years, height: 172.9 cm (SD: 9.07 cm), weight: 77.4 kg (SD: 13.78 kg)). An additional 17 participants were recruited for the control group and were age, height, and weight matched to the ACL participant group ($\bar{x}$ age: 25 (SD: 2.44) years, height: 173.2 cm (SD: 10.52 cm), weight: 75.7 kg (SD: 14.97 kg)). The inclusion criteria for subjects were that they had no history of neuropathy, and had not sustained an injury to their lower extremity in the past six months. Further inclusion criterion for the control group was that they had no previous history of lower extremity injuries and surgeries. The inclusion criterion for the ACL group was unilateral ACLR with a minimum of one-year post-surgery. There were no significant anthropometric differences between groups (p's > 0.05).

2.2. Procedures

Sagittal plane angular knee displacement was collected using two electrogoniometers (Delsys, Boston, MA, USA). Each electrogoniometer was secured over the lateral right and left knee joint and were affixed to the leg using double-sided tape and athletic tape. Electrogoniometers were calibrated with knees in peak extension and knees at 90° flexion using the Delsys Trigno system (Delsys, Boston, MA, USA). Participants performed three trials of over-ground walking at their preferred speed over a distance of 55 m. Wireless timing gates (Brower Timing Systems, Draper, UT, USA) were positioned at the beginning and end of the walking path to calculate the participant's gait speed. The average of the three preferred walking trials was used to determine each individuals' preferred gait speed (100%). Participants were also instructed to walk at four additional target speeds relative to their preferred: 50, 75, 125 and 150%. The order of the different speeds was randomized for each participant. Trials outside of 10% above and below of the intended gait speed were repeated. Each participant repeated a total of 1–4 trials.

2.3. Data analysis

Discrete ϕ is a more appropriate method of quantifying coordination than continuous ϕ, especially when phase plane motion does not approximate a circle and asymmetries may exist between oscillators, as in the case of the knees in the current study (Fuchs et al., 1995). For each stride (i) peak knee flexion was detected for both left and right legs. ϕ was then computed as the ratio of the time between successive peaks of the two legs (Δt) to the stride time (T) of the dominant (Control) or involved (ACL) leg: