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Stride-to-stride variability is altered during backward walking in anterior cruciate ligament deficient patients

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Abstract:

Background: Recently backward walking is used by physical therapists to strengthen the hamstring muscles and thus improve the function of the knee joint of anterior cruciate ligament deficient patients. The aim of this study was to examine the stride-to-stride variability of anterior cruciate ligament deficient patients during backward walking. The variation of how a motor behavior emerges in time is best captured by tools derived from nonlinear dynamics, for which the temporal sequence in a series of values is the facet of interest.

Methods: Fifteen patients with unilateral anterior cruciate ligament deficiency and eleven healthy controls walked backwards at their self-selected speed on a treadmill while three-dimensional knee kinematics were collected (100 Hz). A nonlinear measure, the largest Lyapunov Exponent was calculated from the resulted knee joint flexion–extension data of both groups to assess the stride-to-stride variability.

Findings: Both knees of the deficient patients exhibited significantly lower Lyapunov Exponent values as compared to the healthy control group revealing more rigid movement pattern. The intact knee of the deficient patients showed significantly lower Lyapunov Exponent values as compared to the deficient knee.

Interpretation: Anterior cruciate ligament (ACL) deficiency leads to loss of optimal variability regardless of the walking direction (forwards in previous studies or backwards here) as compared to healthy individuals. This could imply diminished functional responsiveness to the environmental demands for both knees of ACL deficient patients which could result in the knees being more susceptible to injury.

Introduction

Anterior cruciate ligament (ACL) rupture is a common sports injury that is associated with post-traumatic knee instability, functional adaptations (Berchuck et al., 1990), poor control of muscle function or muscle weakness (Tsepis et al., 2004a,b) and ultimately an increased incidence of premature osteoarthritis (Lohmander et al., 2004, 2007). In-vivo biomechanical studies have shown distorted knee joint biomechanics during walking in ACL deficient patients as compared to uninjured knees (Andriacchi and Dyrby, 2005; Georgoulis et al., 2003; Ferber et al., 2004; Moraiti et al., 2007). Additionally, more strenuous pivoting activities have been investigated and relevant studies showed increased tibial rotation in ACL deficient patients when an increased rotational load is applied on the knee joint (Ristanis et al., 2006). However no study has examined backward walking (BW) in ACL deficiency.

Although walking in the backward direction is a relatively novel task for most people, there are several situations during everyday life activities that include backward walking as stepping away from the kitchen sink or positioning in the restroom. Also various sports such as soccer, football, basketball and tennis all incorporate BW during competition. During a soccer match the defender often needs to have some steps in the backward direction to keep visual contact with the attacker of the opposite team. During a tennis match the player has to perform BW or even backward running to obtain the best position in the court before striking the ball. Furthermore, since research suggests that BW can increase energy expenditure to levels high enough to maintain cardiorespiratory fitness (Clarkson et al., 1997; Myatt et al., 1995), BW has been considered an attractive exercise alternative for aerobic training. In recent years there has been a growing interest in the use of BW for injury prevention (Hooper et al., 2004) and for rehabilitation following lower extremity injuries (Myer et al., 2008). On this area the function of the hamstrings muscles during BW has become the center of attention by physical therapists. The electromyographical activity for the biceps femoris and semitendinosus muscles has been found to be considerably higher during BW rather than forward walking (FW) (Grasso et al., 1998; Winter et al., 1989). In BW, the role of the hamstrings is to initiate the swing phase by contracting concentrically (Thorstensson, 1986; Van Deursen et al., 1998; Winter et al., 1989). Specifically, during the early swing phase of BW the main function of the hamstring muscles is to initiate hip extension and knee flexion, thus resulting in greater hamstring activation (Thorstensson, 1986). This increased hamstrings activation during BW has been considered advantageous for training ACL deficient patients with BW by many physical therapists. This is because ACL deficient patients aim to successfully maintain joint stabilization through increased activation of their hamstring muscles (Courtney et al., 2005; Di Fabio et al., 1992; Rudolph et al., 1998). Lastly, another advantage of BW for ACL deficient patients has been considered the concentric contraction of the extensor knee mechanism instead of the more stressful eccentric contraction of these muscles during FW (Thorstensson, 1986). This concentric contraction of the quadriceps during BW leads to less mechanical strain on the knee joint than in FW (Thorstensson, 1986).

However, certain aspects of BW are not yet clearly understood. For example, little is known with respect to gait variability during BW. Winter et al. reported coefficient of variation (CV) values of joint moments and mentioned that joint moments were more variable during BW than FW (Winter et al., 1989). However, traditional linear measures such as the CV can only estimate the magnitude of variability, while the temporal evolution of movement patterns is ignored. In addition, parameters such as joint moments are extensively "treated" algorithmically (i.e. smoothing, differentiation, normalization) to provide with a "mean" picture of the subject's movement pattern. It is obvious that during these procedures the temporal structure of variability is massively distorted (Stergiou et al., 2004a,b). On the contrary, measures from nonlinear dynamics estimate how motor behavior changes over time and provide information about the temporal structure or organization of the movement over time (Stergiou et al., 2004a,b). From a more practical standpoint, these temporal variations of healthy gait represent the underlying physiologic capability of the healthy locomotor system to make flexible adaptations to everyday stresses placed on the human body (Miller et al., 2006). On the contrary, aging (Buzzi et al., 2003) and several neurologic (Dingwell et al., 2000) and orthopaedic (Moraiti et al., 2007) conditions have been shown to alter the deterministic properties of gait variability and lead to diminished functional responsiveness. ACL deficient patients exhibit more repeatable and more rigid walking patterns than the healthy control during FW (Moraiti et al., 2007). It is possible then that ACL deficient patients might show a similar more repeatable and rigid walking pattern during other tasks such as BW. However, it has been shown that FW and BW do not exhibit similar biomechanical patterns but there are differences between these two tasks both for healthy individuals and diseased conditions (Grasso et al., 1998; Hackney and Earhart, 2009; Thorstensson, 1986; Van Deursen et al., 1998; Winter et al., 1989). Thus, it is also possible that ACL deficient patients will respond differently in BW than FW with respect to gait variability. However, the answer to this question is currently unknown.

The purpose of our study was to investigate the stride-to-stride variability during BW in ACL deficient patients in comparison with a matched control group. We used a nonlinear measure, the largest Lyapunov Exponent (LyE), to accomplish our aim. The LyE is a measure of the temporal structure or organization of the variability present in a time series. We hypothesized that the ACL deficient knees exhibit altered structure of the stride-to-stride variability indicated by different LyE values as compared to healthy control knees. Further- more, since a previous study demonstrated that the contralateral intact knee also shows an adaptive behavior to the ACL deficiency by exhibiting decreased LyE values during FW (Stergiou et al., 2004a,b), a secondary hypothesis was that the contralateral intact knee of the ACL deficient patients will exhibit altered LyE values as compared to healthy control knees and ACL deficient knees during BW.

Methods

Subjects

Fifteen subjects (males; mean age 27.1 (SD 4.6) years, mean mass 75 (SD 4) kg, mean height 1.73 (SD 0.09) m) diagnosed with ACL rupture by MRI and clinical examination volunteered for the ACL deficient group. The mean time from injury to examination was 8.1 months (range 1–27). In all patients the diagnosis was later confirmed arthroscopically. All subjects suffered from at least one giving way episode since the time of injury. The symptoms and function of the involved knee joint were estimated with Lysholm score (mean 63, SD 14) (Lysholm and Gillquist, 1982). KT-1000 arthrometer (KT1000; Medmetric Corp., San Diego, CA, USA) was used to measure the anterior tibial translation (side to side differences 9.1, SD 2 mm). Eleven healthy, age and gender-matched subjects (males; mean age 28.3, SD 3.3 years; mean mass 77, SD 8 kg; mean height 1.70, SD 0.07 m) with no history of neuromusculoskeletal injury volunteered as the control group. The mean Lysholm score for the control group was 98 (SD 2) and the side to side difference (SSD) for anterior tibial translation as measured with the KT-1000 was less than 3 mm for all the individuals of the healthy control group (mean SSD 1.45 (SD 0.47)). None of the subjects of the two groups had any previous experience at walking backwards on a treadmill or was involved in activities that required walking or running backward on a regular basis. The study was approved by the Human Studies Committee of our Medical Center. All subjects provided informed consent according to the declaration of Helsinki prior to entering the study.

Protocol

The participants walked backwards on a treadmill (SportsArt 6005; SportsArt America, Woodinville, WA, USA) without using rail support following the exact same procedures. Prior to any data collection, all subjects were given enough time to warm up and familiarize with treadmill BW. For this purpose all subjects were instructed to walk at their preferred selected speed. By using a self-selected pace, any variability changes detected were due to the knee joint condition and not to probable discomfort that may be associated with using a pre-determined speed for all subjects (Diedrich and Warren, 1995; Jordan et al., 2007). The familiarization period was ten minutes which is considered sufficient for the achievement of reliable measurements (Matsas et al., 2000). Once the subjects were comfortable walking backwards on the treadmill at their self-selected pace, kinematics were collected continuously for two minutes. An eight-camera system (VICON, Oxford, UK) was used to capture (100 Hz) the coordinates of 16 reflective markers placed on selected bony landmarks of the lower limbs and the pelvis according to Davis et al. (1991). The same clinician placed the skin markers in all subjects and performed the anthropometric measurements. Using the algorithms described by Davis et al. (1991), we calculated the three-dimensional angular displacement for the knee joint. We only examined the sagittal angular displacement because data from the other planes collected via skin markers are associated with increased error (Cappozzo et al., 1996). Increased amount of measurement error in the data can mask the true structure of stride-to-stride variability and can lead to incorrect conclusions (Rapp, 1994).

Data analysis

Stride-to-stride variability was estimated with the largest Lyapunov Exponent (LyE) for the joint angle time series (both lower extremities were examined for each participant) (Fig. 1; Abarbanel, 1996; Stergiou et al., 2004a,b). Joint angle variability was examined because it has been shown that variability of stride characteristics (i.e. stride time) offers a less sensitive measure of differences between groups than does variability of the joint kinematics (Barrett et al. 2008). Each time series consisted of 12,000 data-points which are considered sufficient for the computation of the LyE (Stergiou et al., 2004a,b). The data were analyzed unfiltered so as to get a more accurate representation of the variations within the system (Mees and Judd, 1993). It was assumed because the same instrumentation was used for all subjects, the level of measurement noise would be consistent for all subjects and thus differences could be attributed to changes within the system itself.
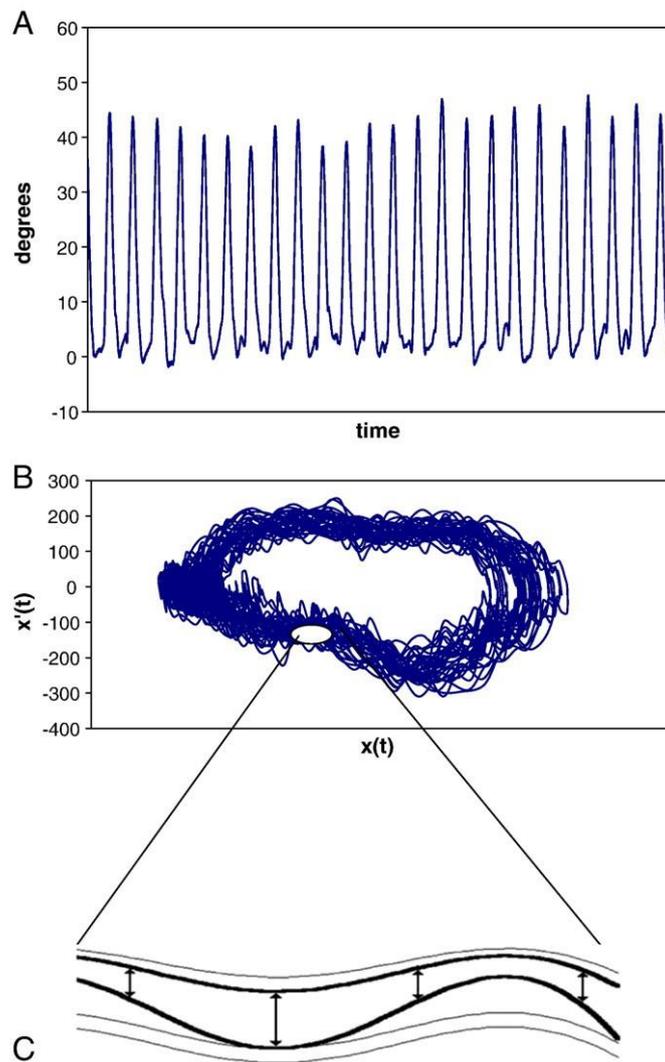
Fig. 1. A graphical representation of the state space and the calculation of the LyE. (A) An original knee angle data set for several strides from FW. (B) A two-dimensional phase space is generated from this entire data set using every single point. (C) A section of the phase space where the divergence of neighboring trajectories is outlined. The LyE is calculated as the slope of the average logarithmic divergence of the neighboring trajectories for the entire time series. It should be noted though that before calculating the LyE, we estimated the number of embedded dimension needed using the global false nearest neighbor (GFNN) analysis [12]. The GFNN calculation revealed that five dimensions is required to reconstruct the phase space from a given time series. The estimation of the embedded dimensions value allowed the calculation of the LyE, which is a measure of the divergence of the data trajectories in phase space, where the phase space is an n-dimensional space with n being large enough to unfold the attractor state [10].

The LyE is a measure of the temporal structure or organization of the variability present in a time series and is calculated as the divergence of the data trajectories in phase space, where the phase space is an n-dimensional space with n being large enough to unfold the attractor state. The LyE describing purely sinusoidal data with no divergence in the data trajectories is zero because the trajectories overlap rather than diverging in phase space. The LyE for random data, which has a lot of divergence in the data trajectories, is relatively large (Abarbanel, 1996; Stergiou et al., 2004a,b). The LyE has been previously used in gait to characterize the underlying structure of variability during movement (Buzzi et al., 2003; Moraiti et al., 2007; Stergiou et al., 2004a,b). A detailed description of the exact procedures utilized for the calculation of the LyE by our group is included elsewhere (Buzzi et al., 2003; Stergiou et al., 2004a,b; Moraiti et al., 2007). Briefly, the LyE for each joint time series and for each subject- condition was calculated using the Chaos Data Analyzer (Professional Version, Physics Academic Software, Raleigh, NC, USA). The Tools for Dynamics (Applied Chaos LLC, Randle Inc., San Diego, CA, USA) was also used for the estimation of the embedded dimensions (was found to be five in this study) which is an important default parameter for the calculation of the LyE (Stergiou et al., 2004a,b).

Statistical analysis

Paired t-tests were used to compare the LyE group means between the two knees of healthy control subjects. There was no significant difference, so the right knee of the healthy control group was used for further comparisons. Paired t-tests were used for the comparison of the LyE group means between the two knees of the ACL deficient patients. Unpaired t-tests were used to compare the LyE group means of the healthy control group to both the ACL deficient knees and the contralateral intact knees of the ACL deficient patients. Unpaired t-test was also used for comparison of the corresponding speeds of BW between control and ACL deficient groups.

Results

No significant differences were noted for the walking speed (mean speed for the control group was 0.55 m/s; mean speed for the ACL deficient group was 0.46 m/s; $P > 0.05$). The ACL deficient knees exhibits significantly lower LyE values as compared to the healthy control knees (mean LyE values for ACL deficient knees 0.142, mean LyE for healthy control knees 0.182, $P < 0.001$). Similarly the contralateral intact knees of the ACL deficient patients (mean LyE values 0.125) showed significantly lower LyE values as compared to the healthy control group ($P < 0.001$). Lastly, the intact knee of ACL deficient patients showed significantly lower LyE values as compared to the ACL deficient knees ($P = 0.0147$; Fig. 2).
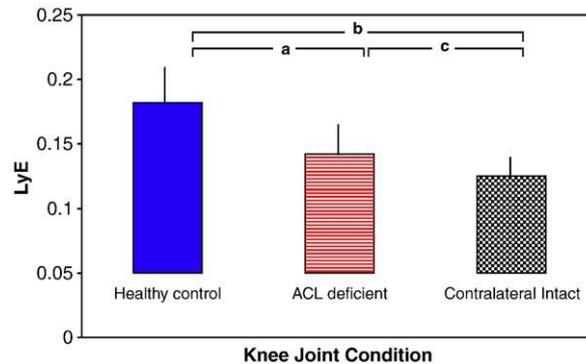
Fig. 2. A bar graph that indicates the group mean Lyapunov exponent (LyE) values and standard deviations for the sagittal angular displacement time series of the knee joint flexion–extension after backward walking (BW) for the three different knee joint conditions: healthy control, ACL deficient and contralateral intact knees. Significant differences were found between the control knee and both ACL deficient and contralateral intact knee. The intact knee showed significantly lower LyE values as compared to the ACL deficient knee. a: $P < 0.001$, b: $P < 0.001$, c: P = 0.0147.

Discussion

The purpose of our study was to investigate the stride-to-stride variability during BW in ACL deficient patients in comparison with a matched control group using the nonlinear measure of LyE. We hypothesized that the ACL deficient knees exhibit altered structure of the stride-to-stride variability indicated by different LyE values as compared to healthy control knees. Furthermore, a secondary hypothesis was that the contralateral intact knee of the ACL deficient patients will exhibit altered LyE values as compared to healthy control knees and ACL deficient knees during BW. Our results supported our hypotheses since the ACL deficient knees showed significantly decreased LyE values as compared to the healthy control knees. In addition, the contralateral intact knees of our patients exhibited significantly decreased LyE values as compared to both the healthy control knees and the ACL deficient knees.

In our study the ACL deficient patients exhibited decreased LyE values as compared to healthy controls revealing movement patterns at the knee that exhibit less divergence and thus more rigidity. In a previous study by Moraiti et al. (2007) the authors investigated the stride-to-stride variability of the knee flexion extension time series for ACL deficient patients during FW and found significantly decreased LyE values for the ACL deficient knees as compared to the healthy control knees (Moraiti et al., 2007). The results of the present study are in accordance to

these of Moraiti et al. The more rigid walking pattern that we found for the ACL deficient knees during BW, theoretically could suggest less capability to respond to different perturbations and to adapt to the changing environment (Stergiou et al., 2006). Since variability represents the underlying mechanisms of the locomotor system and the co-operation among its components, we should expect that any alterations of the components of the locomotor system of the ACL deficient patients could be reflected to the variability of their walking pattern making them drastically different from the healthy controls.

The altered neuromuscular activity that has been previously demonstrated for the ACL deficient patients may account for the more rigid walking patterns that we found for the ACL deficient knees. Berchuck et al. (1990) described the "quadriceps avoidance gait" to characterize the walking pattern of ACL deficient patients, while Tsepis et al. (2004a,b) found significant strength deficits for both quadriceps and hamstrings muscles for these patients. Another explanation of the decreased LyE values noted for the ACL deficient knees could be the loss of the afferent proprioceptive input from the ACL mechanoreceptors after the rupture of the ligament. It has been shown that this deafferentation caused by the ACL deficiency alters reflex pathways to skeletal muscles (Courtney et al., 2005; Di Fabio et al., 1992).

Interestingly, the contralateral intact knee showed significantly more rigid and with less divergence movement patterns during BW as compared to both the healthy control knee and the ACL deficient knee. This is in accordance to previous studies which demonstrated that after ACL rupture biomechanical adaptations occur not only in the ACL deficient knee but also in the intact contralateral knee (Berchuck et al., 1990; Ferber et al., 2004; Moraiti et al., 2007; Stergiou et al., 2004a,b). These studies showed that the intact contralateral knee of the ACL deficient patients exhibits different biomechanics not only as compared to a separate healthy control group (Berchuck et al., 1990; Ferber et al., 2004; Moraiti et al., 2007) but also as compared to the ACL deficient knee (Ferber et al., 2004; Stergiou et al., 2004a,b). Stergiou et al. (2004a,b) showed that while ACL deficient patients walk forward the intact contralateral knee showed more rigid walking patterns as compared to the ACL deficient knee. The results of the present investigation are in agreement with those of Stergiou et al. (2004a,b) and verify their findings during BW. Ferber et al. (2004) reported that all their patients that exhibited bilateral biomechanical accommodations after the ACL rupture, were non-copers, which are patients that report at least one episode of giving way from the time of injury (Rudolph et al., 1998). The authors suggested that these bilateral adaptations may apply only to such patients and that ACL injured subjects who are able to cope with their injury may not exhibit similar bilateral knee joint accommodations. In the present study, all the patients were classified as non-copers, thus supporting the suggestion of Ferber et al. concerning these patients. Except from the bilateral biomechanical accommodations noted for the ACL deficient patients, previous studies reported also a knee joint asymmetry in terms of significant between-limb differences for these patients (Ferber et al., 2004; Rudolph et al., 1998; Stergiou et al., 2004a,b). Rudolph et al. (1998) and Ferber et al. (2004) showed significant differences between the injured and the intact contralat- eral knee of ACL deficient patients regarding the knee joint moments and power patterns, while Stergiou et al. (2004a,b) showed significant differences between the injured and the intact contralateral knee of their ACL deficient patients concerning the stride to stride variability during FW. In the current study we also found significant difference between the ACL deficient knees and the intact contralateral knees. We noticed that although this difference exists between the LyE values of the ACL deficient and the contralateral intact knees, this is not as prominent as the difference that exists between the ACL deficient knees and the controls or compared to the difference noted between the intact knees and the control knees. We believe that these adaptations are made in order to minimize asymmetry between the two knees of ACL deficient patients. The lower LyE values of the intact knee showed that the structure of gait variability for these knees is characterized by increased periodicity and an effort for a more predictable walking pattern which is what is required by the deficient side.

Our results can be interpreted with the "optimal state of movement variability" theoretical model (Stergiou et al., 2006). According to this model healthy human gait is characterized by an optimal state of variability (Stergiou et al., 2006). Any deviation from this optimal state of variability renders the biological system less adaptable to perturbations and environmental demands. A deviation from this optimal state of movement variability can make the system either more rigid and very repeatable or noisy and irregular. According to our results, ACL deficiency results in lower LyE values regardless of the walking direction (FW in Moraiti et al. (2007) or BW in the present study) as compared to that of healthy individuals. This could imply a system that is more rigid and unable to respond to the environmental demands based on the above theoretical model. This impaired variability of the ACL deficient knee could be the reason that this situation is linked to the development of future pathology. Indeed, long follow up studies have shown an increased incidence of osteoarthritis in the ACL deficient knees (Lohmander et al., 2004, 2007). However, it is critical to explore gait variability with longitudinal studies and utilize these sensitive nonlinear measures as an important component of medical assessment.

Our results should be viewed in lieu of the following limitations. Our subjects walked on a treadmill instead of overground. However, it has been demonstrated that comfortable-paced treadmill walking does not diminish the intrinsic stride dynamics of human gait (Chang et al., 2009; Matsas et al., 2000). Furthermore, the collection of a large number of continuous data required for the calculation of stride-to-stride variability and the necessity to make certain the walking speed remains constant over these strides enforce the measurements to be collected on a treadmill. Walking overground is not typically associated with a constant speed for long periods of time (such as in the case with multiple footfalls) due to intermittency (Weinstein, 2001).

In conclusion, we examined the stride-to-stride variability of both knees of ACL deficient patients while walking backwards. According to the results both knees of ACL deficient patients showed a more rigid walking pattern as compared to healthy controls. The contralateral intact knee of ACL deficient patients showed even more rigid walking pattern as compared to the ACL deficient knee. According to these results, ACL deficiency leads to loss of optimal variability regardless of the walking direction (FW in Moraiti et al. (2007) or BW in the present study) as compared to healthy individuals. This could imply diminished functional responsiveness to the environmental demands for both knees of ACL deficient patients which may result in knees more susceptible to injury.

References

Abarbanel, H.D.I., 1996. Analysis of Observed Chaotic Data. Springer-Verlag, New York.

Andriacchi, T.P., Dyrby, C.O., 2005. Interactions between kinematics and loading during walking for the normal and ACL deficient knee. J. Biomech. 38, 293–298.

Barrett, R., Vonk Noordegraaf, M., Morrison, S., 2008. Gender differences in the variability of lower extremity kinematics during treadmill locomotion. J. Mot Behav. 40, 62–70.

Berchuck, M., Andriacchi, T.P., Bach, B.R., Reider, B., 1990. Gait adaptations by patients who have a deficient anterior cruciate ligament. J. Bone Joint Surg. Am. 72, 871–877.

Buzzi, U.H., Stergiou, N., Kurz, M.J., Hageman, P.A., 2003. Nonlinear dynamics indicate aging affects variability during gait. Clin. Biomech. 18, 435–443.

Cappozzo, A., Catani, F., Leardini, A., Benedetti, M.G., Croce, C.D., 1996. Position and orientation in space of bones during movement: experimental artefacts. Clin. Biomech. 11, 90–100.

Chang, M.D., Shaikh, S., Chau, T., 2009. Effect of treadmill walking on the stride interval dynamics of human gait. Gait Posture 30, 431–435.

Clarkson, E., Cameron, S., Osmon, P., McGraw, C., Smutok, M., Stetts, D., et al., 1997.

Oxygen consumption, heart rate, and rating of the perceived exertion in young adult women during backward walking at different speeds. J. Orthop. Sports Phys. Ther. 25, 113–118.

Courtney, C., Rine, R.M., Kroll, P., 2005. Central somatosensory changes and altered muscle synergies in subjects with anterior cruciate ligament deficiency. Gait Posture 22, 69–74.

Davis, R.P., Ounpuu, S., Tyburski, D., Gage, J.R., 1991. A gait analysis data collection and reduction technique. Hum. Mov. Sci. 10, 575–587.

Di Fabio, R.P., Graf, B., Badke, M.B., Breunig, A., Jensen, K., 1992. Effect of knee joint laxity on long-loop postural reflexes: evidence for a human capsular-hamstring reflex. Exp. Brain Res. 90, 189–200.

Diedrich, F.J., Warren Jr., W.H., 1995. Why change gaits? Dynamics of the walk-run transition. J. Exp. Psychol. Hum. Percept. Perform. 21, 183–202.

Dingwell, J.B., Cusumano, J.P., Sternad, D., Cavanagh, P.R., 2000. Slower speeds in patients with diabetic neuropathy lead to improved local dynamic stability of continuous overground walking. J. Biomech. 33, 1269–1277.

Ferber, R., Osternig, L.R., Woollacott, M.H., Wasielewski, N.J., Lee, J.H., 2004. Bilateral accommodations to anterior cruciate ligament and surgery. Clin. Biomech. 19, 136–144.

Georgoulis, A.D., Papadonikolakis, A., Papageorgiou, C.D., Mitsou, A., Stergiou, N., 2003.

Three-dimensional tibiofemoral kinematics of the anterior cruciate deficient and reconstructed knee during walking. Am. J. Sports Med. 31, 75–79.

Grasso, R., Bianchi, L., Lacquaniti, F., 1998. Motor patterns for human gait: backward versus forward locomotion. J. Neurophysiol. 8, 1868–1885.

Hackney, M.E., Earhart, G.M., 2009. Backward walking in Parkinson's disease. Mov. Disord. 24, 218–223.

Hooper, T.L., Dunn, D.M., Props, J.E., Bruce, B.A., Sawyer, S.F., Daniel, J.A., 2004. The effects of graded forward and backward walking on heart rate and oxygen consumption. J. Orthop. Sports Phys. Ther. 34, 65–71.

Jordan, K., Challis, J., Newell, K., 2007. Walking speed influences on gait cycle variability. Gait Posture 26, 128–134.

Lohmander, L.S., Ostenberg, A., Englund, M., Roos, H., 2004. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum. 50, 3145–3152.

Lohmander, L.S., Englund, P.M., Dahl, L.L., Roos, E.M., 2007. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am. J. Sports Med. 35, 1756–1769.

Lysholm, J., Gillquist, J., 1982. Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. Am. J. Sports Med. 10, 150–154.

Matsas, A., Taylor, N., Mcburney, H., 2000. Knee joint kinematics from familiarized treadmill walking can be generalized to overground walking in young unimpaired subjects. Gait Posture 11, 56–63.

Mees, A.I., Judd, K., 1993. Dangers of geometric filtering. Physica D 68, 427–436.

Miller, D.J., Stergiou, N., Kurz, M.J., 2006. An improved surrogate method for detecting the presence of chaos in gait. J. Biomech. 39, 2873–2876.

Moraiti, C., Stergiou, N., Ristanis, S., Georgoulis, A.D., 2007. ACL deficiency affects stride- to-stride variability as measured using nonlinear methodology. Knee Surg. Sports Traumatol. Arthrosc. 15, 1406–1413.

Myatt, G., Baxter, R., Dougherty, R., Williams, G., Halle, J., Stetts, D., et al., 1995. The cardiopulmonary cost of backward walking at selected speeds. J. Orthop. Sports Phys. Ther. 21, 132–138.

Myer, G.D., Paterno, M.V., Ford, K.R., Hewett, T.E., 2008. Neuromuscular training techniques to target deficits before return to sport after anterior cruciate ligament reconstruction. Review. J. Strength Cond. Res. 22, 987–1014.

Rapp, P.E., 1994. A guide to dynamical analysis. Integr. Physiol. Behav. Sci. 29, 311–327.

Ristanis, S., Stergiou, N., Patras, K., Tsepis, E., Moraiti, C., Georgoulis, A.D., 2006. Follow- up evaluation 2 years after ACL reconstruction with bone-patellar tendon–bone graft shows that excessive tibial rotation persists. Clin. J. Sports Med. 16, 111–116.

Rudolph, K.S., Eastlack, M.E., Axe, M.J., Snyder-Mackler, L., 1998. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. J. Electromyogr. Kinesiol. 8, 349–362.

Stergiou, N., Buzzi, U.H., Kurz, M.J., Heidel, J., 2004a. Nonlinear tools in human movement. In: Stergiou, N. (Ed.), Innovative Analyses of Human Movement. Human Kinetics Publ, Champaign, IL, pp. 63–90.

Stergiou, N., Moraiti, C., Giakas, G., Ristanis, S., Georgoulis, A.D., 2004b. The effect of the walking speed on the stability of the anterior cruciate ligament deficient knee. Clin. Biomech. 19, 957–963.

Stergiou, N., Harbourne, R.T., Cavanaugh, P.T., 2006. Optimal movement variability: a new theoretical perspective for neurologic physical therapy. J. Neurol. Phys. Ther. 30, 120–129.

Thorstensson, A., 1986. How is the normal locomotor program modified to produce backward walking? Exp. Brain Res. 61, 664–668.

Tsepis, E., Giakas, G., Vagenas, G., Georgoulis, A., 2004a. Frequency content asymmetry of the isokinetic curve between ACL deficient and healthy knee. J. Biomech. 37, 857–864.

Tsepis, E., Vagenas, G., Giakas, G., Georgoulis, A., 2004b. Hamstring weakness as an indicator of poor knee function in ACL-deficient patients. Knee Surg. Sports Traumatol. Arthrosc. 12, 22–29.

Van Deursen, R.W., Flynn, T.W., McCrory, J.L., Morag, E., 1998. Does a single control mechanism exist for both forward and backward walking? Gait Posture 7, 214–224.

Weinstein, R.B., 2001. Terrestrial intermittent exercise: common issues for human athletics and comparative animal locomotion. Am. Zool. 41, 219–228.

Winter, D.A., Pluck, N., Yang, J.F., 1989. Backward walking: a simple reversal of forward walking? J. Mot Behav. 21, 291–305.