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# The Effect of Anterior Cruciate Ligament Reconstruction on Stride-to-Stride Variability

Constantina O. Moraiti
*University of Ioannina*

Nicholas Stergiou
*University of Nebraska at Omaha*, nstergiou@unomaha.edu

Stavros Ristanis
*University of Ioannina*

Haris S. Vasiliadis
*University of Ioannina*

Kostas Patras
*University of Ioannina*

***See next page for additional authors***

**Authors**
Constantina O. Moraiti, Nicholas Stergiou, Stavros Ristanis, Haris S. Vasiliadis, Kostas Patras, Cassandra Lee, and Anastasios D. Georgoulis

# The effect of anterior cruciate ligament recontruction on lower extremity relative phase dynamics during walking and running

Max J. Kurz, Nicholas Stergiou, Ugo H. Buzzi, Anastasios D. Georgoulis

M. J. Kurz, N. Stergiou, U. H. Buzzi
HPER Biomechanics Laboratory,
University of Nebraska at Omaha,
Omaha, NE 68182-0216, USA
E-mail: mkurz@mail.unomaha.edu
Tel.: +1-402-5542670
Fax: +1-402-5543693

A. D. Georgoulis
Orthopaedic Sports Medicine Center of Ioannina,
University of Ioannina Medical School,
451 10 Ioannina, Greece

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**Abstract**

The purpose of this investigation was to use relative phase dynamics to evaluate gait in individuals with a reconstructed anterior cruciate ligament (ACL) during walking and running. Relative phase dynamics can describe the coordination strategies between the interacting segments at the lower extremity. Ten subjects who had undergone ACL reconstruction using the central third of their patellar tendon and ten healthy controls walked and ran on a treadmill at a self-selected pace. Relative phase dynamics were calculated for the foot–shank and shank–thigh coordinative relation- ships. Statistical differences between the groups were noted for the foot– shank relationship ($p$<0.05) during both walking and running and for the shank–thigh relationship ($p$<0.05) during walking. Our results indicate that current ACL reconstructive techniques may result in altered relative phase dynamics. These changes in relative phase dynamics could be related to a loss of sensory information about joint position and velocity that is typically provided by the intact ACL. Additionally, relative phase adaptations could be a learned response from the early stages of postsurgical rehabilitation. Relative phase dynamics provide quantitative information about the dynamic status of the ACL-reconstructed knee that cannot be gained from the conventional time-series evaluation of gait analysis data. Relative phase dynamics measures should supplement the conventional gait analysis measures that are used today for the clinical evaluation of the functional dynamic stability of the reconstructed knee. The examination of relative phase dynamics could be clinically important for the quantification of new ACL surgical interventions and of patient performance at various stages of rehabilitation. Further research should incorporate relative phase dynamics to understand the influence of ACL reconstruction on coordination and functional patient outcomes.

## Introduction

Anterior cruciate ligament (ACL) rupture is a common knee injury in sports that usually results in surgical reconstruction [19, 27]. Surgical reconstruction is performed to re-establish the mechanical properties of the knee in the hope of returning the patient to an active lifestyle. Clinically, the health and performance of the reconstructed knee is typically evaluated with an arthrometer (e.g., KT-1000) and strength-testing devices [8, 33]. However, such measures provide only a static evaluation of the reconstructed knee; they do not quantify the dynamic performance of the reconstructed knee during daily living activities such as locomotion. Furthermore, it has been shown that clinical outcome measures, such as questionnaires, thigh circumference, and isometric force, are not sensitive enough to predict functional performance [1, 30, 39]. Hence, gait analysis has recently become more prevalent as a clinical measure to quantify the postsurgical status of the ACL-reconstructed knee.

Pre- and postsurgical differences in gait biomechanics following an ACL reconstruction have been documented [4, 6, 11, 12, 14, 35]. However, the underlying mechanical and biological mechanisms responsible for these differences are not well understood. Several authors have also suggested that ACL reconstructed patients will regain preinjury gait characteristics over time [4, 6, 11, 12]. However, no investigation has provided clear scientific evidence that ACL reconstructed patients do return to a normal gait pattern. Additionally, there is growing concern that abnormal gait patterns in the ACL reconstructed population may result in osteoarthritis [22]. Thus, there still exists clinical uncertainty as to whether the ACL reconstructed knee can return to its presurgical functional capacity.

Review articles by Johansson et al. [21] and Friden et al. [13] present considerable scientific evidence that the ACL is more than just a mechanical device that is used to stabilize the knee in extreme positions. The ACL contains mechanoreceptors that provide joint velocity and position feedback to the central nervous system via the c-muscle spindle system. Such feedback influences muscle activity patterns of the surrounding knee musculature throughout the gait pattern. Feedback from the $\gamma$-muscle spindle system is necessary for maintaining proper joint coordination during gait. Potentially, the lack of evidence that ACL patients return to presurgical status may be related to a loss of sensory feedback in the reconstructed joint that is necessary for normal gait. A loss of sensory information from the ACL may result in errors in the normal joint coordinative patterns during gait [21]. It is unknown whether current surgical techniques may eliminate such sensory information that is necessary for proper lower extremity coordination. Therefore, further exploration of the relationship between ACL reconstruction and lower extremity coordination is warranted.

Currently, gait analysis of the ACL-reconstructed knee relies on conventional angular position–time, velocity–time, or angle–angle presentations. However, such presentations do not reveal the direct relationship between velocity changes and position [5, 37, 38]. It is important to evaluate this relationship in an ACL-reconstructed knee since the ACL provides sensory feedback on both velocity and position [13, 21]. Furthermore, quantification of interjoint (e.g., thigh–shank) coordination is very difficult with the above-mentioned presentations [5, 9, 32, 34]. However, proper interjoint coordination is crucial for locomotion, and the ACL contributes maximally to this via its mechanical and physiological properties [13, 21]. The usage of relative phase dynamics can solve the above problems. Relative phase dynamics can provide a better quantification of gait analysis data and they can reveal the functional joint stability of the ACL-reconstructed knee throughout the gait pattern [2, 5, 16, 18, 23, 32]. It has also been shown that relative phase dynamics are more revealing of the health of the lower extremity joints than conventional gait analysis measures (e.g., angle–time presentations) [2]. As Winstein and Garfinkel [38] have suggested, relative phase dynamics can provide a window of particular types of causal motor control processes that are not usually revealed by conventional time-based plots. Thus, relative phase dynamics have been used for the following purposes:

- To explain muscle mechanoreceptor contribution to ankle movements [15]
- To examine the effect of the Q-angle on lower extremity movements and patellofemoral pain syndrome [16, 18]
- To evaluate the effect of rehabilitation on hemiplegic gait [24]
- To examine the effects of fatigue on low back pain during a repetitive lifting task [34]

- To identify changes in forearm movement coordination in patients with Parkinson's disease [36]
- More recently, to evaluate knee stability during hop- ping following an ACL reconstruction [37].

Specifically, relative phase dynamics utilizes the displacements and velocities of the segments that surround the joint to quantify the joint's coordination. For example, the continuous relative phase, a measure from relative phase dynamics, quantifies the coordination between the shank and thigh segments that compose the knee joint. Such a measure is appealing for quantifying postsurgical gait because it can provide insight into changes in joint coordination that may be due to mechanical or sensory changes in the ACL-reconstructed knee.

Additional studies are necessary to elucidate whether ACL reconstruction returns the patient to a healthy and functional state. Relative phase dynamics can provide answers to the clinical status of the ACL-reconstructed knee that were not evident in prior biomechanical investigations. As such, the purpose of this investigation was to use relative phase dynamics to evaluate the coordinative joint strategies used by postsurgical ACL-reconstructed individuals while walking and running. We hypothesized that compared with healthy controls, individuals with ACL reconstruction would display altered relative phase dynamics while walking and running. Such information can help in guiding future rehabilitative and surgical techniques necessary to return the ACL patient to a pre-injury state.

**Materials and methods**

*Subjects*

Ten subjects, who had undergone ACL reconstruction on their right knee at an average of 10 months (2–24) after injury using the central third of their patellar tendon, participated in this investigation (seven females, three males; mean age 23.9 years; mean mass 81.1 kg; mean height 177.3 cm). The same orthopedic surgeon performed all ACL reconstructive operations. In some cases, meniscal damage and other ligamentous damage had also been present at the time of injury. These injured tissues were also repaired during the ACL reconstruction surgeries. At the time of investigation, all the subjects had completed knee rehabilitation and had returned to full functional activity. Testing of the ACL-reconstructed subjects was per- formed an average of 3.4 years after surgery. Ten healthy gender- and age-matched subjects who had never suffered any kind of orthopedic or neurological condition volunteered for the control group (mean age 21.7 years; mean mass 67.2 kg; mean height 171.9 cm). All subjects in this investigation had prior treadmill walking and running experience. Prior to testing, each subject read and signed an informed consent that was approved by the University Institutional Review Board.

*Protocol*

The subjects walked and ran on a motorized treadmill while sagittal plane kinematic data of the lower extremity were collected using a 60-Hz camera. Prior to videotaping, reflective markers were positioned on the subject's right lower extremity. The placement of the reflective markers was as follows: (a) greater trochanter, (b) axis of the knee joint as defined by the alignment of the lateral condyles of the femur, (c) lateral malleolus, (d) outsole of the shoe approximately at the bottom of the calcaneus, and (e) outsole of the shoe approximately at the fifth metatarsal head. The subjects were allowed to warm up on the treadmill for a minimum of 8 min. During the warm-up session, each subject established a self-selected comfortable walking and running pace. The subjects were instructed to select a pace similar to a pace that would be used when performing continuous aerobic walking and running. This self-selected pace was used for all conditions. Once the subject felt comfortable walking or running on the treadmill, 15 consecutive footfalls (trials) were collected for further analysis. Between each condition, the subjects were allowed a minimum of 5 min of rest. The average walking speeds were 1.21 m $s^{-1}$ (SD=0.19) for the ACL group and 1.23 m $s^{-1}$ (SD=0.17) for the control group. The average running speeds were 2.26 m $s^{-1}$ (SD=0.45) for the ACL group and 2.33 m $s^{-1}$ (SD=0.24) for the control group. A comparison between the two groups for the walking and the running speeds revealed no statistically significant differences ($p$>0.05).

Joint markers were digitized using the Peak Performance Technologies' Motus system (Peak Performance Technologies, Englewood, CO, USA). The stance period of each gait cycle was parsed out of the entire data series using a customized laboratory software. We selected the stance period for analysis because the ACL is under its greatest stress during this portion of the gait cycle [40]. The obtained kinematic positional coordinates of the sagittal markers were scaled and smoothed using a Butterworth low-pass filter with a selective cut-off algorithm based on Jackson [20]. From the plane coordinates obtained, the angular displacements and velocities of the sagittal foot, shank, and thigh were calculated relative to the right horizontal axis. All kinematic data were normalized to 100 points for the stance period using a cubic-spline routine to enable mean ensemble curves to be derived for each subject condition.

*Continuous relative phase measures*

Phase portraits for the respective segments were created by plotting the segment's angular position versus its angular velocity [2, 38] (Fig. 1). The trajectories were then transformed from Cartesian ($x$, $y$) to polar ($r$, $\Theta$) coordinates, where the radius was $r=(x^2+y^2)^{1/2}$ and the phase angle was $\Theta=\tan^{-1}[y/x]$. Figure 1 depicts a specimen phase portrait and the calculated phase angle $\Theta$. A complete tutorial with qualitative explanations of the configurations of different phase portraits for disordered human locomotion is provided by Winstein and Garfinkel [38].

The phase angles were used to calculate the relative phase dynamics between the two segments that surround the joint. The continuous relative phase (CRP) represents the dynamic interactions of the two segments for every point during gait [2, 16, 18, 23, 24, 32]. Essentially, it represents the phasing relationships or coupling between the actions of the two segments that surround the joint. CRP was calculated by subtracting the phase angles of the corresponding segments throughout the stance period: $\varphi_{SHANK-THIGH} = \Theta_{SHANK} - \Theta_{THIGH}$, $\varphi_{FOOT-SHANK} = \Theta_{FOOT} - \Theta_{SHANK}$, where $\varphi$ is the relative phase between the two interacting segments, and $\Theta$ is the phase angle of the respective segment. CRP values closer to 0° indicate that the two segments are moving in a similar fashion, or they are closer to being in phase.

Values closer to 180° indicate that the two segments are moving in the opposite direction or they are closer to being out of phase. The CRP curves for each segmental relationship (shank–thigh and foot–shank) were averaged across footfalls (trials), and mean ensemble curves were generated for all subject conditions.

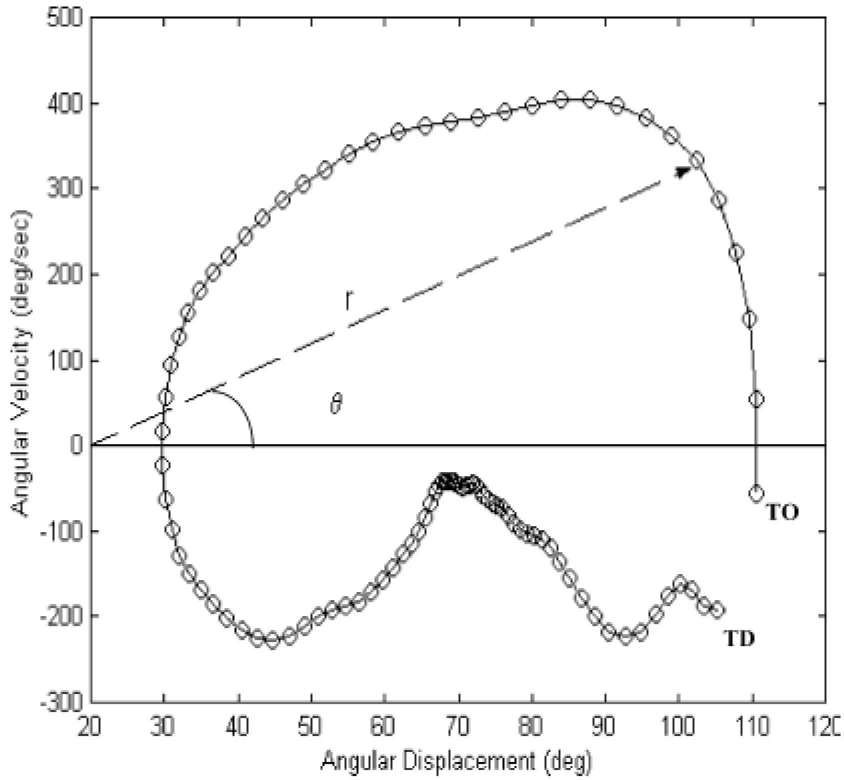


**Fig. 1** A representative phase portrait that is composed by the angular displacement and velocity of the rotating shank segment during the running gait cycle. The Cartesian $(x, y)$ coordinates of the trajectories are obviously angular displacement and velocity. If we translate the Cartesian coordinates of the trajectory to polar coordinates $(r, \theta)$, we have radius $r = (x^2 + y^2)^{1/2}$ and phase angle $\theta = \tan^{-1}[y/x]$. The angle $(\theta)$ is practically formed between the horizontal and the radius $(r)$ and is referred to as the phase angle of the trajectory. *TD* represents touch down and *TO* represents toe off

To better illustrate the above, let us consider the following example. Let us assume that the thigh and the shank are in contact. Now the two segments will have to move away from each other (i.e., simultaneous hip extension and knee extension) and then back together with the same velocity. This task illustrates a perfect out-of-phase relationship between the segments with respect to one another. The values of the CRP will be closer to 180°. Now let us assume that the thigh and shank are not in contact with each other. Now both segments will have to move in the same direction (i.e., either clockwise or simultaneous hip flexion and knee extension) with the same velocity and then both segments will have to reverse their actions at the same time. This task illustrates a perfect in-phase relationship between the segments with respect to one another. The values of the CRP will be closer to 0°. During locomotion, the segments continuously move between these coordinative relationships in a completely dynamic fashion. CRP can quantify these coordinative relationships between the rotating segments.

The relative phase curve configurations provide unique graphical insights into the coordination dynamics of the segments that comprise the joint. The slope of the relative phase curve configuration indicates which segment is moving faster during periods of the gait cycle. A positive slope indicates that the distal segment is moving faster in phase space, while a negative slope indicates that the proximal segment is moving faster in phase space [2]. The minimum and maximum of the relative phase curve throw light on changes in coordination between the two segments as they represent reversals in the coordination dynamics [2]. A change in the segment leading the other in phase space is defined as a reversal. Additionally, changes in the timing of the reversals and the number of reversals have also been used previously to provide insight into joint coordination in normal and pathological gait patterns [2, 16, 18, 23, 24, 32].

To statistically test differences between the curves, it was necessary to characterize the curves by a single number. Therefore, the mean absolute value of the ensemble CRP curve values (MARP) was calculated by averaging the absolute values of all points of the entire ensemble curve (Eq. 1):

$$\mathrm{MARP} = \frac{\sum_{p=1}^{P} |\phi_p|}{p}$$

where $|\varphi|$ is the absolute relative phase between two segments and $p$ is the number of points in the mean ensemble curve (e.g., 100). A low MARP value indicated that the two interacting segments exhibit a coordinative relationship which is closer to being in phase, while a high MARP value indicated that the two interacting segments exhibit a coordinative relationship which is closer to being out of phase.

*Statistics*

Group means and standard deviations were calculated for the MARP of each segmental relationship (foot– shank and shank–thigh) for the two conditions. Statistical differences between the two groups (ACL-reconstructed vs. control) while walking and running were noted with independent *t*-tests ($p<0.05$).

**Results**

Evaluation of the graphical configuration of the CRP curves for walking and running indicated that the ACL-reconstructed individuals and the healthy controls had different locomotive strategies (Figs. 2 and 3). During walking (Fig. 2a), the values of the foot–shank coupling are closer to 0°, which means that the two segments exhibit a relationship which is closer to being in phase.
Inspection of the timings of the minimums and maximums of the relative phase curve indicated that the reversal in the coordination dynamics of the foot–shank relationship was similar between the two groups. This was evident from the similar configuration of the curves of the two groups (Figs. 2a and 3a). However, the magnitudes of the minimums and maximums were not similar. These differences would suggest that the coordination dynamics at the ankle joint were influenced by ACL reconstruction.

There were additional differences between the shank– thigh relative phase dynamics while walking (Fig. 2b). These differences were most pronounced in the late portion of the stance period, where the ACL-reconstructed subjects had a more out-of-phase relationship (values closer to 180o). The magnitude of the negative slope of the relative phase curve during the later portion of the stance indicated that the proximal segment was moving faster than the distal segment for the ACL-reconstructed subjects. Based on these graphical observations, it is apparent that the knee joint coordination was different between the two groups while walking.

During running (Fig. 3a), the foot–shank relative phase dynamics appeared to be quite different throughout the stance period. Compared with the healthy controls, the ACL-reconstructed subjects generally had an out-of-phase relationship during the early and late portions of the stance period. The timing of the segment reversal at the maximum was quite different between the two groups. The ACL-reconstructed subjects had a maximum earlier in the stance period. Such altered timing of the segmental reversal suggests that the ACL- reconstructed subjects changed the coordinative relationship between the foot and the shank earlier than the healthy controls. Furthermore, the slope of the relative phase curve during the late portion of the stance phase was quite different between the two groups. The magnitude of the negative slope in the ACL-reconstructed subjects indicated that the shank segment (proximal segment) was moving faster. These graphical observations indicate that the ankle joint had altered coordination dynamics during the running stance period.

Graphically, the coordination dynamics for the shank–thigh coupling were also different during the running condition (Fig. 3b). In the early portion of the stance period, the ACL-reconstructed subjects have an out-of-phase relationship in the shank–thigh coordination dynamics (values start at 80°). However, the healthy controls have an in-phase relationship (values start at 0°). Therefore, early in stance the coupling between the shank and the thigh is different between the two groups. This is also the case in late stance where the ACL-reconstructed subjects again exhibit an out-of-phase relationship (values at toe off at 80°), while the shank–thigh coupling is in phase in the healthy controls (values at toe off at 20°). There were also graphical differences in the timings and the magnitudes of the relative phase minimums and maximums. Specifically, the ACL-reconstructed subjects exhibit an earlier segmental reversal in early stance (earlier minimum) and are not capable of performing the segmental reversal at the late stance (lack of a maximum). These graphical observations suggest that the reversals in the coordination dynamics of the shank– thigh coupling during the running stance period were quite different between the two groups.

Statistically significant MARP differences between the groups were noted for both the foot–shank ($p<0.05$) and the shank–thigh ($p<0.05$) relationship during walking (Table 1). During running, significant differences between the two groups were noted only for the foot–shank coupling ($p<0.05$).

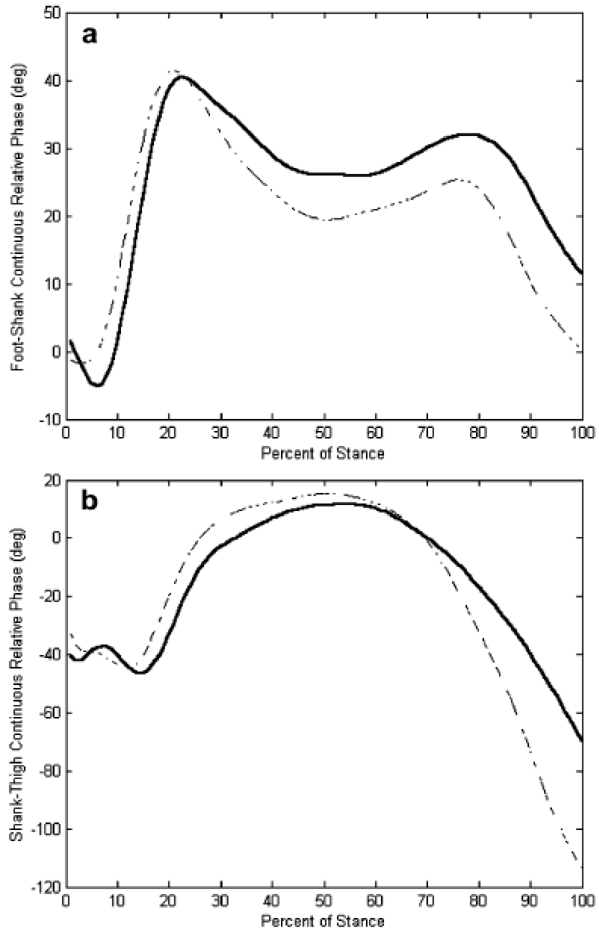


**Fig. 2** Mean ensemble CRP dynamics for the foot–shank (**a**) and the shank–thigh (**b**) couplings during the stance period of walking. The *bold line* represents the healthy control group, and the *dashed line* represents the ACL-reconstructed group

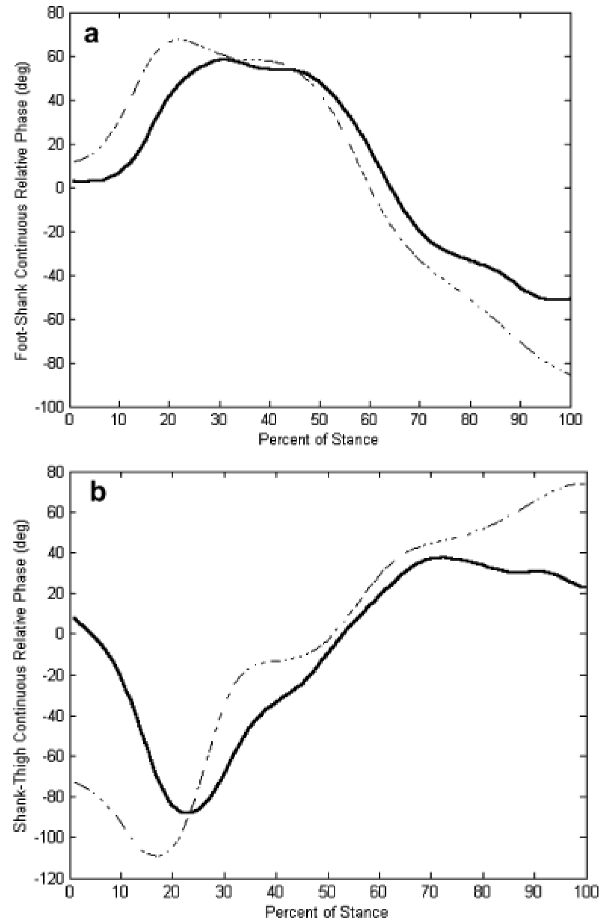


**Fig. 3** Mean ensemble CRP dynamics for the foot–shank (**a**) and the shank–thigh (**b**) relationships during the stance period of running. The *bold line* represents the healthy control group, and the *dashed line* represents the ACL-reconstructed group

**Discussion**

In the present study, we hypothesized that, compared with healthy controls, individuals with ACL reconstruction would display altered relative phase dynamics while walking and running. This hypothesis was supported by the results of this investigation. These results coincide with previous investigations that have noted that ACL-reconstructed individuals have altered post-surgical lower extremity locomotive strategies [4, 6, 8, 10–12, 35]. Several of these investigations have suggested that ACL-reconstructed patients will return to pre-injury gait status over time [4, 6, 11, 12]. However, our data were not supportive of this assumption. Current ACL reconstructive techniques appear to result in altered relative phase dynamics. It has been previously shown that altered coordinative strategies of the surrounding musculature may enhance the loads imposed on the knee and alter the knee's stability [21]. The coordination changes seen in this investigation can result in improper loads on the reconstructed knee joint and a lack of proper stability. In essence, these factors could have a long-term effect that can lead to osteoarthritis in the joint.

A mechanism responsible for the observed differences in coordination seen in this investigation could be the lack of sensory information provided by the reconstructed knee. It has been shown that after ACL reconstruction, sensory and behavioral changes were still present [3]. This is due to the fact that the ACL provides sensory information about joint position and velocity to the central nervous system via the $\gamma$-muscle spindle system [13, 21]. Such information is necessary to regulate joint coordination and joint stability during gait. The inability of patients to return to the pre-injury gait patterns could be due to loss of sensory information in the reconstructed ACL. New surgical techniques should attempt to solve this problem. Such a solution could be a two-bundle graft that has been shown to simulate better the morphology of the original ACL [17, 26]. Theoretically, a two-bundle reconstruction has several advantages over a single-bundle reconstruction with respect to regaining a structure that more closely resembles a normal ACL, morphologically and functionally. This technique, however, has not been investigated dynamically, and future research work focused on $\gamma$ -muscle spindle sensory information from the reconstructed ACL and joint coordination should be performed to determine the advantages of two-bundle anatomic reconstruction.

The results of this investigation also indicated that changes in gait following ACL reconstruction are not localized at the knee joint. During walking and running, the ACL-reconstructed individuals displayed significantly different adaptations that encompassed both the ankle and the knee joint. These findings are supportive of previous investigations that have found adaptations at the other lower extremity joints following ACL reconstruction [4, 6, 10–12, 35]. Different relative phase dynamics at the other joints could be adaptations learned during the early stages of postsurgical rehabilitation. These adaptations could be related to mechanisms for avoiding knee pain experienced early in rehabilitation. As much of the clinical assessment focuses on the stability of the ACL-reconstructed knee, these postsurgical lower extremity adaptations usually go unnoticed. Therefore, postsurgical clinical assessment should encompass the entire lower extremity.

No significant differences were evident for the shank–thigh relative phase dynamics while running. Graphically the mean ensemble from all the subjects suggested that there were differences between the groups (Fig. 3b). However, the large standard deviations seen in Table 1 indicate that there was a considerable amount of variability in the shank–thigh relative phase dynamics within each group during the running condition. With the number of subjects included in this investigation, such variance may have hindered the ability to detect statistical differences between the two groups. We would suggest that a larger sample size may provide conclusive results to clarify whether differences exist between the two groups' shank–thigh relative phase dynamics during running. An alternative explanation is that during running, the inertial forces of the rotating segments are much higher. Thus, it is possible that they can ''overwrite'' the sensory feedback provided by the reconstructed ACL. Therefore, adaptations that were evident in walking are now masked due to the increased inertial forces that drive the rotations of the lower extremity segments.

Traditional clinical measures of joint function in ACL-reconstructed individuals have been based on arthrometer (e.g., KT-1000) and strength-measuring testing [6, 24]. Such testing provides a clinical assessment of the static stability of the knee. However, such measures provide only a static evaluation of the reconstructed knee and do not quantify the dynamic performance of the reconstructed knee during daily living activities such as locomotion [1, 21, 29, 30, 39]. Thus, the dynamic lower extremity adaptations that occur as a result of ACL reconstruction could go unnoticed. Although a rehabilitated ACL-reconstructed knee could have acceptable strength and static stability, the dynamic behavior of the knee during activities of daily life (i.e., locomotion) could be altered. This is why gait analysis has recently become much more prevalent as a clinical measure to quantify the postsurgical status of the ACL-reconstructed knee. However, even gait analysis has several shortfalls. A major one is that it relies on conventional time-series presentations that do not reveal interjoint coordination differences or direct relationships between velocity changes and position [5, 9, 32, 34]. However, it is well established that receptors exist within the ACL that provide crucial sensory information for controlling both position and velocity of the rotating segments [13, 21, 25]. Relative phase dynamics of the lower extremity that can be calculated from the gait analysis data can overcome the above-mentioned shortfalls and can provide important information about the control processes of the reconstructed ACL during dynamic activities such as locomotion [2, 5, 16, 18, 23, 32]. This information can be used to investigate post-surgical adaptations regarding the coordinative actions of the two segments. It can also provide a better way to classify the stages of rehabilitation and various ACL surgical interventions.

A limitation of the present study is that our evaluation of the phase dynamics of the lower extremity was conducted only for the sagittal plane. However, we chose to examine only sagittal plane data because kinematic data from the other two planes, collected via skin markers, have been associated with an increased amount of error [7, 28, 29]. Specifically, Reinschmidt et al. [28] compared skin markers and bone pins during running and found good agreement only for knee flex- ion/extension. For the other two planes of motion, they identified that the average errors relative to the knee range of motion were 63% for internal/external rotation and 70% for abduction/adduction. Even though walking involves less skin movement than running, the errors could still be substantial. Increased amount of measurement error in the data can mask true statistical differences and can possibly lead to incorrect conclusions derived from kinematic data.

**Table 1** Mean (SD) absolute relative phase (MARP) for the ACL-reconstructed and healthy control groups

| Group | Foot–shank CRP | Shank–thigh CRP |
|---|---|---|
| Walk | | |
| ACL | 25.7 (2.3)* | 22.6 (4.9)* |
| Control | 21.2 (2.7) | 30.2 (4.8) |
| Run | | |
| ACL | 38.6 (7.2)* | 49.1 (11.8) |
| Control | 48.3 (9.6) | 52.2 (20.0) |

*A significant difference in the CRP dynamics at the 0.05 alpha level

## Conclusion

Individuals with an ACL reconstruction display altered relative phase dynamics during the stance period while walking and running. These changes are related to a loss of sensory information that is usually provided by the ACL and to lower extremity adaptations learned during rehabilitation. Based on the results of this investigation, relative phase dynamics measures can quantify lower extremity coordination during gait. Such information should supplement the conventional gait analysis measures that are used today for the clinical evaluation of functional dynamic stability of the reconstructed knee. Furthermore, the examination of relative phase dynamics could be clinically important for the quantification of new ACL surgical interventions and of patient performance at various stages of rehabilitation. Further research should incorporate relative phase dynamics to understand the influence of ACL reconstruction on coordination and functional patient out- comes.

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