3-2001

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A DYNAMICAL SYSTEMS INVESTIGATION OF LOWER EXTREMITY COORDINATION DURING RUNNING OVER OBSTACLES

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ABSTRACT

Objective: To investigate intralimb coordination during running over a level surface and over obstacles of three different heights. **Design:** The phasing relationships between the foot and leg motions in the frontal plane, and the shank and thigh motions in the sagittal plane were used to compare patterns of coordination. **Background:** The coordinated actions of lower extremity segments are necessary to absorb the impact forces generated during running. The behavioral patterns of these segments can be studied under changing task demands using analysis techniques from the Dynamical Systems Theory. **Methods:** Ten subjects ran at their self-selected pace under four conditions: over a level surface and over obstacles of different heights (5%, 10%, 15% of their standing height). A force platform was used to record impact forces during landing after obstacle clearance, while kinematics were collected using a two-camera system. **Results:** The increases in obstacle height resulted in significant changes in impact forces (34% increase between the two extreme conditions) and more in-phase relationships between the segments during early-stance. No changes were observed in the variability of the phasing relationships. **Conclusions:** The coordination changes observed might be compensatory strategies aimed to reduce forces and potential injury. However, since the impact forces still increased significantly, it is also possible that the observed changes might be at-risk movement patterns predisposing runners to injury.

RELEVANCE

Tools from the Dynamical Systems Theory, such as intralimb coordination, can be used as a way to evaluate running mechanics so that comparisons can be made to various patient populations in subsequent studies. This approach might be a viable alternative to examine questions in therapeutics.

Keywords: impact forces, dynamical systems, lower extremity, coordination, obstacle, running

INTRODUCTION

Recreational running is a very popular form of physical activity [1, 2, 3]. Benefits from running range from improvement of cardiovascular performance to reducing the occurrence of osteoporosis in elderly women [1]. Unfortunately, negative side effects in terms of musculoskeletal injuries (stress fractures, patellar pain syndrome, etc.) are also associated with running [2]. Quantitatively, the frequency of running-induced injuries to the skeletal system is considerable (2.5-12.1/1000 hrs running; [2]). These injuries are classified as overuse and involve the knee, leg, ankle, and foot [2, 3].

However, as it has been frequently documented in the medical literature, there has been little significant progress made in expanding our understanding of running injury mechanisms [2, 4-7] . The medical literature suggests that the lack of single measures to predict specific running injuries may be due to the multifactorial nature of running injuries [2, 4, 6, 8-10]. Running is a complex motor skill that involves numerous interacting components or degrees of freedom. It is the mastery of these degrees of freedom that results in a stable coordinated movement. Coordination, then, is defined as the process by which the degrees of freedom are organized in time and in sequence to produce a functional movement pattern [11, 12]. It is perhaps in the patterns of coordination, not individual biomechanical variables that the insight to running injury mechanisms may be found.

In motor control, stable coordination patterns have been considered a fundamental feature of consistent, functional action [11, 12, 13]. An alternative approach to understand the construction of, and subsequent change in, patterns of coordination comes from the Dynamical Systems Theory (DST; 12, 13). Briefly, DST proposes that change from one coordinated motor pattern, to a different coordinated pattern is discontinuous and occurs when a variable to which the neuromotor system is sensitive is scaled up or down through a critical threshold. This variable is referred to as a control parameter and changes in its value cause the neuromotor system to move through different behavioral states. An example comes from the work of Kelso [13]. The task was the alternate flexion and extension of the forefinger on each hand. The task began with the forefingers pointing in the same direction. Thus, one finger was flexed while the other was extended. Under slow oscillation speeds, the fingers maintained this orientation, and out of phase relationship, with respect to one another. Upon scaling up on the oscillation speed, however, a behavioral transition occurred such that both fingers flexed at the same time and then went into extension at the same time, an in-phase relationship. Just prior to the transition, greater instability was observed in the phasing relationship between the fingers.

In running, it is the coordination and phasing relationships between the actions of the shank and the thigh in the sagittal plane that produce flexion and extension at the knee joint. In the frontal plane, the actions of the leg and the foot have to be coordinated to produce pronation and supination at the subtalar joint. To understand the adaptation to changing task demands, we look at the functional patterns of coordination in the lower extremity for signs of instability.

Furthermore, the actions of knee flexion and pronation occur during the first 50% of the stance period [14, 15] and they are important to attenuate impact forces. The large magnitudes of impact forces have been implicated as a primary cause of running injuries [3, 6, 16-18]. By acting eccentrically, the knee joint muscles attenuate 70% of the impact forces [17]. Subtalar pronation allows for the impact forces to be absorbed during a longer period by the supporting structures reducing these forces. Without the mechanisms of knee flexion and subtalar pronation, these forces would have to be abruptly and directly absorbed by the supporting structures, causing problems associated with excessive stress [14, 16, 19].

However, limited research exists in the running literature where coordination between the interacting segments has been examined especially under varied conditions that can possibly increase impact forces. An example of such varied conditions can be the presence of obstacles in the training path, which is often associated with increased impact forces. Such perturbation may also produce instability between the actions of the interacting segments or a transition to a new behavioral pattern. Either change may reduce the capacity to absorb the increased impact forces. Theoretically [16], deviations in loading may lead to soft tissue and bone pathology if the musculoskeletal system fails to adapt to the increased loading demands.

The purpose of this study was to investigate intralimb coordination during running over a level surface and over obstacles of three different heights. To accomplish this purpose, we used DST analysis techniques, and we examined the phasing relationships between the foot and leg motions in the frontal plane, and the shank and thigh motions in the sagittal plane.

METHODS

Subjects

Ten healthy males (n = 7) and female (n = 3) runners who had been running a minimum of 10 miles per week for at least one year volunteered as subjects (mean age: 25.9 years; mean body mass: 74.0 kg; mean height: 177.7 cm). All subjects exhibited a heel-toe footstrike pattern during running at a comfortable self-selected pace. Prior to testing, each subject read and signed an informed consent document approved by the University of Oregon Human Subjects Review Board.

Instrumentation

A force platform (AMTI, Advanced Mechanical Technology Inc., Watertown, MA, USA) was used to measure the vertical ground reaction forces. The force platform was installed in the middle of a 30 m runway in the Biomechanics Laboratory at the University of Oregon. An AMTI signal conditioner/amplifier was employed in conjunction with the force platform. The signal conditioner/amplifier was interfaced with an Ariel Performance Analysis System (APAS, ARIEL Dynamics Inc., Trabuco Canyon, CA, USA) containing a 32-channel analog to digital sampling module. The APAS was interfaced to an 80386-processor computer. One channel of the force signal (Fz, vertical component) and one synchronizing channel, sampled at 1000 Hz.

Kinematic data were collected using two NEC (NEC USA Inc., Nashville, TN, USA) high speed video cameras (200 Hz) interfaced to a real time automated video based tracking system (Motion Analysis Corporation, Santa Rosa, CA, USA). The cameras were positioned to obtain a right sagittal and rear (frontal) view of the right lower extremity during stance. Camera distances were 14 and 11 meters, respectively and each was used in conjunction with a 10x12A zoom lens to optimize image size while minimizing perspective error. Prior to recording the movement, reflective markers were placed on the subject's right lower extremity. Specifically, the sagittal view markers were placed as follows: a) lateral malleolus, b) knee joint center, and c) greater trochanter. Rear (frontal) view markers were placed as described by Edington et al [15]. The retroreflective images from each camera were obtained and translated to cartesian coordinates using a Motion Analysis VP320 video processor interfaced to an 80486-processor computer. Data collection by the APAS and the video tracking system was triggered by a manual transistor/transistor/logic (TTL) switch to synchronize the video and force data.

Procedures

Running speed was monitored over a 3 m interval using a photocell timing system. Subjects were given time to accommodate to the experimental set up and to adequately warm-up prior to testing. Warm-up consisted of running through the testing area without concern for stepping on the force platform. During warm-up the subject established a comfortable running pace which was recorded. This speed (+/-5%) was used as a baseline speed for subsequent testing. Following this procedure a foot placement marker was located approximately 10 m before the timed interval to allow for a normal right foot contact on the force platform. Each trial consisted of a run of approximately 40 m. Data transfer from the cameras to the computer and the qualitative inspection of the force curves allowed for a 1 min inter-trial rest interval.

All subjects were asked to run at their previously established baseline pace under four different conditions. The first condition was running on a level surface while the other three conditions were running over obstacles of three different heights: 5, 10, and 15 percent of their standing height. The obstacles were placed directly before the force platform so that the subject had to clear the obstacle with the right leg and land on the force platform. While the subjects were performing at their self-selected pace, a piece of athletic tape was positioned one step before the force platform to identify left foot position. When the obstacle was placed on the runway, the subjects were instructed to hit the tape with their left foot prior to clearing the obstacle with the right leg. Using this procedure insured that the subjects did not change their stride length when clearing the obstacle. The subjects were also instructed to run over the obstacles and avoid jumping over them, in order to maintain a normal heel-toe running pattern. The obstacles were made of light weight wood so that if a subject stepped on or hit the obstacle by mistake while running, the obstacle was destroyed. This minimized subjects' fear for tripping and falling. Each condition consisted of ten trials for a total of 40 trials.

The order of the presentation of conditions was predetermined starting with the no obstacle condition followed by the obstacle conditions presented from the lowest to the highest obstacle. The rationale for using this predetermined order was based on DST, where scaling up in a continuous fashion of the control parameter (obstacle height) will result in changes reflected on the phasing relationships. Therefore, an order effect is actually desirable [20-22]. In addition, the obstacle heights were established based upon the related literature [23, 24].

Data Reduction

A typical vertical ground reaction force (Fz) plot from a heel-strike runner exhibits three distinct points [18]: the first maximum value which is the ground reaction impact force (IF), the second maximum value or ground reaction active force (AF) and the minimum value between the two maximums (Fmin). These three points were identified for each trial by the same investigator using laboratory software. This software allows identification of both the values and the corresponding times. The IF values and the times from contact to Fmin (TFmin), to AF (TAF), and to toeoff (Toff) were retained for further analysis. The IF values were normalized to body mass, and the mean value was calculated for each subject-condition. Group means were also calculated for each condition. The TFmin and TAF values were normalized to percent of stance by dividing them by Toff values and multiplying the result by 100. The normalized TFmin and TAF values were averaged for each subject-condition and across conditions.

The normalized TFmin and TAF values were used to identify two distinct periods from the stance phase: the impact period which is from contact to Fmin, and the active period which is from Fmin to AF. Separate examination of each period was utilized since measurements over the entire stance can mask differences for a single period. Functionally, TAF is synchronous with maximum knee flexion [14, 15] and it is the transition point from braking of the forward motion to propulsion. At this point the subtalar joint is changing from pronation to supination. TFmin divides the braking of the forward motion into two periods. The impact period is time matched with the occurrence of the impact phenomena [18]. The active period is associated with the aftermath of impact, the active loading, and the conclusion of the absorption period of the ground reaction forces by the musculoskeletal structures [18]. The focus of this study is on changes in intralimb coordination and impact forces. Thus, the analysis is limited to the dependent variables associated with the time of occurrence of the impact phenomena - the impact and the active period.

All kinematic coordinates were scaled and smoothed using a Butterworth Low-Pass Filter with a selective cut-off algorithm based on Jackson [25]. The cut-off values used were 13-16 and 16-20 Hz for the sagittal and the frontal view coordinates, respectively. Subsequently, from the frontal plane coordinates, the foot and leg absolute (regarding the left horizontal) angular positions and velocities were calculated. From the sagittal plane coordinates, the shank and thigh absolute (regarding the left horizontal) angular positions and velocities were calculated. All kinematic parameters 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.

To examine intralimb coordination the phase portraits for the foot, leg, shank and thigh were generated. The phase portrait is a plot of each segment's position versus its velocity. The phase portrait analysis follows Rosen's [26] suggestion that the behavior of a dynamical system may be captured by a variable and its first derivative with respect to time. After the phase portraits were constructed, the resulting phase plane trajectories were used to calculate the phase angles $\varphi = \tan^{-1}[x'/x]$ [12, 13, 26, 27]. To allow for the calculation of the phase angles, the phase plots were normalized according to Li et al. [27].

Subsequently, the normalized phase angles of the segments' trajectories were used to examine phasing relationships. From the frontal plane, the foot and leg can be viewed as rotating clockwise and counterclockwise around the subtalar joint axis, while for the sagittal plane, the shank and the thigh can be viewed as rotating clockwise and counterclockwise around the knee joint axis. Continuous relative phase (CRP) represents the phasing relationships or coordination between the actions of the two interacting segments at every point during a specific time period; i.e., it depicts how the two segments are coupled in their movements while performing the task. CRP was calculated throughout stance by subtracting the phase angles of the corresponding segments: $\varphi_{\mathrm{FRONTAL\ REL.\ PHASE}} = \varphi_{\mathrm{FOOT}} - \varphi_{\mathrm{LEG}}$ and $\varphi_{\mathrm{SAGITTAL\ REL.\ PHASE}} = \varphi_{\mathrm{SHANK}} - \varphi_{\mathrm{THIGH}}$. Values close to zero degrees indicate that the two segments are moving in a similar fashion or in-phase, while values close to 180 degrees indicate that the two segments are moving in opposite directions or out-of-phase. The CRP curves for each segmental relationship (frontal and sagittal) were averaged across trials and mean ensemble curves were generated for all subject-conditions. To statistically test differences between CRP curves, it was necessary to characterize the curves by single numbers, therefore, two additional parameters were calculated using the ensemble curves.

The first parameter was the mean absolute value of the ensemble CRP curve values (MARP). It was calculated by averaging the absolute values of the ensemble curve points for the designated periods (impact and active).

where p = number of points in each of the two periods

Functionally, a low MARP value indicates a more in-phase relationship between the two segments' actions for this condition and for this given subject. The second parameter was the deviation phase (DP) and was calculated by averaging the standard deviations of the ensemble CRP curve points for the designated periods (impact and active).

where p = number of points in each of the two periods

Functionally, a low DP value indicates a less variable relationship between the two segments' actions for this condition and for this given subject. The normalized times of TFmin and TGRAF identified from the Fz plots were used to calculate the MARP and DP parameters for each of the two periods. Group means were also calculated for MARP and DP for each segmental relationship, for each period, and for each condition.

Statistical Analysis

One-way repeated measures ANOVAs (obstacle height with subjects as the repeated factor) were performed on the subject means for IF, MARP, and DP. For MARP and DP, statistical analysis was performed for each coordinative relationship (foot-leg for frontal and shank-thigh for sagittal) and for each period (impact and active). In tests that resulted in a significant F-ratio ($P<0.05$), a Tukey multiple comparison test was used to identify the significant differences.

RESULTS

The group analysis results are presented in Table 1. The IF group results were statistically significant, with the post-hoc analysis revealing statistical differences among all possible comparisons. It can be observed that the higher the obstacle, the greater the IF. The significant increases in IF allowed for the evaluation of the other dependent variables over a wide range of impact force increases.

INSERT TABLE 1 ABOUT HERE

The DP group results were not statistically significant for either the frontal or the sagittal segmental relationships (Table 1). The MARP group results were statistically significant for both frontal and sagittal segmental relationships during the impact period (Table 1). No statistical differences were found for the active period. In the impact period and for the frontal segmental relationship, the no obstacle condition resulted in the highest value and was statistically different from both the 10% and 15% obstacle conditions. For the sagittal, the lowest value was produced by the 10% obstacle condition and it was statistically different from the 15% and no obstacle conditions. The greatest MARP value was produced for the no obstacle condition indicating that the introduction of the obstacle decreased the MARP values.

To better understand the above significant findings we looked at the phase portraits of the individual segments and the ensemble CRP curves. Comparing the phase portraits of the frontal foot and leg motions, the leg trajectory shows greater change in its geometric form between conditions (Figure 1). It can also be observed that an additional cycle is emerging within the original leg cyclic pattern. This additional cycle can be clearly observed in the 5% and 10% obstacle conditions. Every time that the trajectory goes through zero a segmental reversal is observed. Thus, the leg segment changed its oscillatory direction twice during stance. The foot trajectories are more similar geometrically, and the foot segment changed its direction only once during stance.

INSERT FIGURE 1 ABOUT HERE

The frontal CRP ensemble curves of the same subject are displayed in Figure 2. For all conditions, CRP begins around +100 deg (Figure 2). A positive value indicates that the foot is leading the leg. Toward midstance the two segments are in-phase (zero deg), while during late stance the relationship is reversed with the leg leading. This is indicated by the negative values. The effect of the obstacle in the first portion of stance is quite interesting. In all obstacle conditions, CRP goes through zero more than once (Figure 2). That means that the obstacle caused the two segments to move in-phase in early stance, followed with the foot regaining the lead for a while, before eventually the two segments go through in-phase again and the leg obtaining the lead. These phenomena are consistent with the emergence of the additional cycles identified in the leg phase portraits.

INSERT FIGURE 2 ABOUT HERE

Comparing the phase portraits of the sagittal shank and thigh motions, the thigh trajectory shows greater change in its geometric form between conditions (Figure 3). It can be seen that the introduction of the obstacle caused an additional cycle to be developed within the original cyclic pattern during early stance. This additional cycle increased in size as obstacle height increased and showed that the thigh reversed its oscillation twice during stance. The increasing height of this vertical loop just after foot contact indicates rapid and abrupt changes in the thigh's segmental behavior. The shank trajectories are more similar geometrically and without reversals, indicating a backward only rotation around the knee joint during stance.

INSERT FIGURE 3 ABOUT HERE

The sagittal CRP ensemble curves of the same subject are displayed in Figure 4. For the no obstacle condition, CRP begins around -40 deg indicating that the thigh is leading the shank (Figure 4). Toward midstance the two segments are in-phase (zero deg), while during late stance the relationship is reversed with the shank leading the thigh. The introduction of the obstacle resulted in changes mainly in early stance. For all obstacle conditions, relative phase started at zero deg indicating an in-phase relationship at foot contact. This result indicates that when the obstacle was present, both segments moved backwards at foot contact, while later the thigh reversed its motion forward and then backwards again. The formation of the additional cycles observed for the thigh phase portraits, also supports this explanation.

INSERT FIGURE 4 ABOUT HERE

DISCUSSION

The purpose of this study was to investigate intralimb coordination during running over a level surface and over obstacles of three different heights. To accomplish this purpose, we used DST analysis techniques. This approach requires one to follow a specific methodology to give the DST ideas a concrete meaning [12, 13, 20-22]. The first step is to characterize the movement patterns using the appropriate variables, the order parameters. Then, it is important to identify control parameters that move the system through its behavioral states, so when a control parameter reaches a critical threshold a transition to a new coordinative behavior will occur. Changes of the control parameter are reflected upon the order parameter and therefore reveal the dynamics of the system.

In the present study, this procedure was used. Thus, the phasing relationship of limb segments (continuous relative phase) within the same leg was used as the order parameter. Based upon the literature [12, 21, 22], the use of continuous relative phase was the logical choice since it incorporates both the periodic and the coupling motion of the segments involved. The height of an obstacle that a runner had to avoid was used as a control parameter. This proposal was driven by the premise that IF would increase as obstacle height was increased. The results supported our idea and showed that IF increased significantly with increases in obstacle height (Table 1).

Subsequently, we examined the order parameters for any changes caused by the scaling up of the suggested control parameter. The results revealed changes both statistically and graphically. The partitioning of the stance period also assisted in locating the statistical changes. Both frontal and sagittal relative phase, described by MARP, significantly decreased during the impact period. These decreases indicate that the interacting segments became more in-phase, reducing the independent action of each segment. Since these changes occurred during the impact period, they may be related to the increased IF. Graphically, the appearance of additional cycles for the leg (frontal) and the thigh (sagittal) trajectories might indicate the emergence of a new coordinated patterns. The CRP values and curves found in this study for level running were similar with those presented by other authors [22, 27].

An interesting observation is that the changes of the control parameter were not reflected statistically on the order parameter in terms of changes in variability. DP was used as a measure to describe the variability of the phasing relationship. The fact that DP did not change but MARP decreased during impact, it suggests that the variability of the system remained constant. The system was maintaining itself by maintaining the variability of the segmental couplings.

These changes in the system's behavior can be accommodative in nature. Since the IF increased, the system has to use some compensatory strategies aimed to reduce forces and potential injury. However, such adaptations were probably not sufficient in the present study because IF still increased significantly (17.73 N/kg to 26.47 N/kg; Table 1). It is well established from the footwear related research [18, 28, 29], that adaptations are usually the reason for the lack of significant differences in IF when shoes of various hardness are compared. In such experiments the individuals tested, usually changed their kinematics to maintain small IF when they run with harder shoes. However, in the present study the adaptive mechanisms used were not enough because the IF increased drastically. An alternative explanation is that the observed changes of coordination could be at-risk movement patterns predisposing runners to injury. However, it should be mentioned that comparisons to patient populations should be made to draw such conclusions and gain insight into possible injury mechanisms.

A limitation of this study concerning the frontal relationships is how representative a two-dimensional biomechanical evaluation of the subtalar joint is since it is a three-dimensional phenomenon. The literature [30, 31] indicates that the differences between the two types of analyses are minimal after foot contact and through approximately 80% of stance. Differences increase as the foot moves out of plane with maximum differences occurring during toeoff. Since the focus of this study is from early- to mid-stance, a two-dimensional analysis was considered adequate. However, future studies should consider validating our results with a three-dimensional analysis.

Both subtalar pronation and knee flexion have been presented as mechanisms to decrease IF during running [14, 16, 17, 19]. Since IF have been implicated as a major cause of running injuries, it is of great importance to optimally execute these motions. Improper coordination between the actions of the two joints might limit the ability of the lower extremity as a shock absorbing system. However, limited research examining the coordinative actions of these two joints has been accomplished. DST has been proposed as an alternative approach to therapeutics [12, 32, 33]. As Winstein and Garfinkel [34] suggested a phase plane analysis cannot only be used to describe movement, but can provide a window into control processes. Traditional time series analysis may not be able to reveal such information. By examining the phase portraits of the interacting segments changes in coordination can be observed. The usage of phase portraits and subsequently of continuous relative phase, allows the incorporation of both angular displacement and velocity to examine coordination and movement [12, 32]. This paper utilized this approach and examined intralimb coordination during running. It was found that IF increased with increases in obstacle heights. The increased IF affected the phasing relationships of both the shank-thigh (sagittal) and foot-leg (frontal) segmental relationships during early stance.

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Variables	No Obstacle	5% Obstacle	10% Obstacle	15% Obstacle
IF (N/Kg)	17.73 $^{5\%O, 10\%O, 15\%O}$ (2.24)	20.42 $^{10\%O, 15\%O}$ (2.94)	23.20 $^{15\%O}$ (3.88)	26.47 (4.97)
Sagittal MARP Impact (deg)	50.40 $^{10\%O}$ (7.27)	45.75 (9.39)	43.83 $^{15\%O}$ (10.24)	49.56 (9.24)
Sagittal MARP Active (deg)	54.03 (7.16)	55.46 (9.18)	56.54 (8.42)	54.31 (7.91)
Frontal MARP Impact (deg)	77.75 $^{10\%O, 15\%O}$ (11.94)	68.66 (9.17)	58.41 (9.40)	60.72 (7.98)
Frontal MARP Active (deg)	20.21 (9.11)	16.61 (7.84)	21.20 (9.60)	24.23 (14.48)
Sagittal DP Impact (deg)	7.25 (1.79)	7.81 (2.61)	8.33 (2.99)	9.83 (2.68)
Sagittal DP Active (deg)	7.74 (2.47)	8.39 (1.97)	8.35 (3.03)	9.49 (3.28)
Frontal DP Impact (deg)	24.53 (7.37)	21.68 (6.29)	23.05 (11.51)	26.69 (12.27)
Frontal DP Active (deg)	23.12 (8.12)	23.68 (14.61)	20.90 (9.94)	23.89 (12.43)

FIGURE LEGENDS

Figure 1. Phase portraits of the frontal foot (top panel) and leg (bottom panel) motions from a representative subject for all conditions. The first 80% of stance is plotted. The occurrence of foot contact (FC) is also identified.

Figure 2. Frontal (foot-leg) relative phase from the same representative subject for all conditions. Each curve is an ensemble average over all trials. The no obstacle condition is represented by a solid line, while the obstacle conditions with markers (5% circles; 10% squares; 15% triangles).

Figure 3. Phase portraits of the sagittal shank (top panel) and thigh (bottom panel) motions from the same representative subject for all conditions. The first 80% of stance is plotted. The occurrence of foot contact (FC) is also identified.

Figure 4. Sagittal (shank-thigh) relative phase from the same representative subject for all conditions. Each curve is an ensemble average over all trials. The no obstacle condition is represented by a solid line, while the obstacle conditions with markers (5% circles; 10% squares; 15% triangles).