Intralimb coordination following obstacle clearance during running: the effect of obstacle height

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Abstract

The purpose of this study was to investigate the different coordination strategies used following obstacle clearance during running. Ten subjects ran over a level surface and over obstacles of six different heights (10, 12.5, 15, 17.5, 20 and 22.5% of their standing height). Analysis based upon the dynamical systems theory (DST) was used and the phasing relationships between lower extremity segments were examined. The results demonstrated that the increasing obstacle height elicited behavioral changes. The foot and the leg became more independent in their actions, while the leg and the thigh strengthened their already stable relationship. The 15% obstacle height seems to be a critical height for the observed changes. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Running is a very popular form of recreation and exercise. It is also a very complex motor skill that involves numerous interacting components or degrees of freedom. Mastering these degrees of freedom can lead to a stable, coordinated and skillful movement. Thus, coordination can be defined as the process by which the degrees of freedom are organized in time and in sequence to produce a functional movement pattern [1,2]. In motor control, stable coordination patterns are considered a fundamental feature of consistent, functional action [2–5]. A contemporary approach to understand the construction of, and subsequent change in, patterns of coordination comes from the dynamical systems theory (DST). In DST, coordinated patterns are constructed out of the constraints applied to the neuromotor system. These constraints come from the organism (e.g. joint flexibility, perceptual abilities), the environment (e.g. running on flat versus uneven terrain), and the task (e.g. running at slow or fast speeds). The constraints effectively reduce the number of degrees of freedom and simplify the management of the neuromotor system. The motor output is shaped by the constraints applied to the system. This approach to movement coordination contrasts with theories that suggest that all the details of a movement’s execution are specified a priori by an action plan in the central nervous system.

Essential for DST is the notion of stability, which refers to the behavioral state of a system. Under the DST, when a system is slightly perturbed, it will return spontaneously to a stable state. These stable states of movement systems are known as attractors. Attractors are preferred patterns and they represent stable areas of movement around which behavior tends to occur when a system is allowed to operate in its preferred manner [2,3]. Examples of such movement patterns are walking, running, etc. If one tries to walk at an extremely slow pace, the movement is highly dis-coordinated and of poor efficiency, thus unstable. DST emphasizes the identification of variables that can help us investigate the dynamics of the attractors. These variables are the order parameter and the control parameter. The order parameter is observed over time to determine whether it demonstrates a stable pattern. If it does indeed show a
stable pattern, an attractor can be identified [2,3,5]. Thus, order parameters are functionally specific and define the overall behavior of the system. They allow a coordinated movement pattern to be reproduced and distinguished from other patterns. In gait, the relative phase between segments of the same limb that describes intralimb coordination has been suggested [2,3,5] as a reasonable choice of an order parameter.

While order parameters are functionally-specific to a coordinated movement pattern, nonspecific control parameters change freely according to the characteristics of the situation or environment. Under research conditions, an experimenter systematically alters a control parameter to see its effect on the stability of the order parameter. This allows for the determination of attractor states for patterns of limb movement. Change from one attractor state to another occurs when a control parameter reaches a critical threshold. For example, the change from walking to running in every individual occurs when speed reaches a specific value [3].

The scalar changes of the control parameter are reflected upon the order parameter and reveal the dynamics of the attractor in terms of stability. An attractor’s stability is defined as the dynamic property that describes the variability of the order parameter. The size of the stability of an attractor can be measured by the variance or standard deviation of the order parameter. Large variations are synonymous with decreased stability or lack of coordination which can eventually result in a change to a new attractor state. A classic example of this abrupt change from one attractor state to another comes from the work of Kelso [3]. The task was the alternate, yet simultaneous, 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, an 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 lower extremity segments that produce movements such as flexion and extension. However, limited research exists in the running literature where coordination between the interacting segments has been examined, especially under varied conditions. An example of such varied conditions can be the presence of obstacles in the running path. Past studies have examined how humans safely walk over obstacles [6–10]. These researchers focused on mechanisms used to clear different obstacle heights and/or widths and also observed how vision can influence the locomotor act. Less attention has been given to obstacle clearance by other modes of locomotion, such as running [11].

Research [12,13] in running has identified, that 90% of the population use a heel strike landing pattern during jogging. Bates et al. [12] observed that most runners during a jogging pace contact the surface on the lateral side of the heel. However, during sprinting many of the heel strike runners change to a forefoot strike [14,15]. It is possible that this change may be a mechanism to decrease impact forces and increase mechanical efficiency [16]. Research on landing after vertical jumps has also identified a forefoot strike landing which was attributed to the increased impact with the ground [17,18]. No attention has been directed toward the evaluation of the kinematics of the leading leg while running over high enough obstacles to cause a heel strike runner to land on the forefoot. The investigation of the lower extremity coordination during running over obstacles may enhance understanding of control of locomotion.

The purpose of this study was to investigate the different strategies used following obstacle clearance during running. To accomplish this purpose, the subjects ran over obstacles of various heights and the data evaluation was based upon the DST. Thus, the phasing relationships between the foot, the leg, and the thigh motions in the sagittal plane were examined.

2. Methods

2.1. Subjects

The subjects for this investigation were ten healthy male (N = 4) and female (N = 6) recreational runners (age = 23.5 years; mass: 67.5 kg; height: 173.9 cm). Before the subjects were admitted to this research study, the investigator qualitatively analyzed their running style to ensure that they preferred a jogging pace with a heel strike pattern. Prior to testing, each subject provided informed consent on a form approved by the Institutional Review Board of the University of Nebraska.

2.2. Instrumentation

A sagittal view of the right lower extremity was obtained for all trials using a HSC-180N video camera with a sampling frequency of 180 Hz. The video camera was located 8 m perpendicular to the running pathway. A zoom lens was used in conjunction with the video camera to optimize image size and minimize perspective error. Reflective markers were placed on the right lower
extremity to identify the following landmarks: (a) right head of the fifth metatarsal; (b) right heel underneath the calcaneus; (c) right lateral malleolus; (d) right lateral joint line of the knee; and (e) greater trochanter of the right hip. An additional marker was positioned at the obstacle to assist in determining the location of the obstacle in the field of view. The video images were stored on SVHS video tapes via a HSR-180N SVHS video camera recorder, which was interfaced with a Magnavox TV for an instant qualitative evaluation of the video recording. The video data were transformed to digital format and digitized via the PEAK MOTUS video system. A single camera was used because sagittal view measures of running correspond well in two- and three-dimensions [19,20]. Ground reaction force data were also collected using a force platform. These data were addressed elsewhere [21].

2.3. Protocol

Subjects wore their regular running shoes to assure the most normal performance. Running speed was monitored over a 3-m interval using a photo-electronic 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, a 40-m runway with a 0.6-m wide lane, without concern for stepping on the force platform. During warm-up, the subject established a comfortable running speed, which was recorded. This speed (± 5%) was used for the subsequent testing and a trial was considered acceptable only when the running speed was within this predetermined range. Following this procedure a foot placement marker was located approximately 7 m before the timed interval to allow for a normal right foot contact on the force platform. Each trial was visually monitored to insure that the stride was normal and the foot was completely on the force platform. The type of foot strike was also qualitatively evaluated and recorded. Every subject ran at the previously established comfortable self-selected pace over obstacles of six different heights: 10, 12.5, 15, 17.5, 20, and 22.5% of the subject’s standing height. In addition, a baseline condition with no obstacle was collected. The obstacle heights were established based upon pilot work and previous literature [11]. The obstacle’s width was 75 cm constituting as such a bilateral obstruction. The obstacle was placed directly before the force platform so that the subject was forced to clear the obstacle with the right leg and land on the force platform. While the subjects performed at their self-selected pace, a marker 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 marker with their left foot prior to clearing the obstacle with the right leg. This procedure insured that the subjects did not change their stride length when clearing the obstacle. By controlling the stride length and, as mentioned above, the speed, one ensured that the observed changes were due only to the obstacle perturbation. It has been documented in the literature [22,23] that changes in stride length and in speed can affect the mechanics of the leading leg. Thus, they could also affect measures of intralimb coordination. To minimize the risk of the subject tripping and/or falling, the obstacles were made of extremely lightweight wood and were destroyed when a subject accidentally stepped on or hit the obstacle while running. Each condition consisted of ten trials.

2.4. Data reduction and analysis

All kinematic coordinates were scaled and smoothed using a Butterworth low-pass filter with a selective cut-off algorithm based on Jackson [24]. The cut-off values used were 8–14 Hz. Subsequently, from the planar coordinates, foot, leg, and thigh angular displacements and velocities were calculated (Fig. 1). All kinematic parameters were normalized to 100 points for the pre-landing (PL) and the stance (S) period, respectively, using a cubic spline routine to enable mean ensemble curves to be derived for each subject-condition. The PL period was identified as the time elapsed between the frame that the x-coordinate of the metatarsal marker was larger than the x-coordinate of the obstacle marker, to the touchdown frame. The S period was identified using the force data. Since the kinetic and kinematic data files were time matched, the identified touchdown and toe off timing occurrences

Fig. 1. Identification of angles.
from the force data were used to determine the corresponding frames in the video data.

To examine intralimb coordination the phase portraits for the foot, leg, and thigh were generated. The phase portrait is a plot of each segment’s displacement versus its velocity. The phase portrait analysis follows Rosen’s [25] 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 \( \phi = \tan^{-1}[v/x] \) [25,26]. To allow for the calculation of the phase angles, the phase plots were normalized [26]. Phase plots were normalized to minimize amplitude differences between the segments. Angular displacement curves were normalized such that the midpoint of the segments range of motion was located at the origin and the extreme were located at \( \pm 1 \). Angular velocity values were normalized by the maximum absolute velocity of the curve, such that zero velocity was maintained at the origin.

Subsequently, the normalized phase angles of the segments’ trajectories were used to examine phasing relationships. The foot and leg can be viewed as respectively rotating clockwise and counterclockwise around the ankle joint axis, while the leg and the thigh can be viewed as rotating clockwise and counterclockwise around the knee joint axis. Relative phase 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). Relative phase was calculated throughout the S period by subtracting the phase angles of the corresponding segments: \( \phi_{\text{ANKE REL PHASE}} = \phi_{\text{FOOT}} - \phi_{\text{LEG}} \) and \( \phi_{\text{KNEE REL PHASE}} = \phi_{\text{LEG}} - \phi_{\text{THIGH}} \). Values close to 0° indicate that the two segments are moving in a similar fashion or in-phase, while values close to 180° indicate that the two segments are moving in opposite directions or out-of-phase. Furthermore, positive values indicate that the distal segment’s phase angle is greater than the proximal segment’s phase angle (i.e., the foot is leading in its trajectory or the leg is lagging). The usage of relative phase allows the incorporation of both angular displacement and velocity to examine coordination and movement. This approach is advantageous since there is evidence that receptors exist within the muscles and tendons for controlling both position and velocity [27].

The relative phase curves for each segmental relationship (ankle and knee) were averaged across trials and mean ensemble curves were generated for all subject-conditions. The subject mean ensemble curves were also averaged across subjects to generate group mean ensemble curves for all conditions. However, to statistically test differences between relative phase curves, it was necessary to characterize the curves by single numbers. Therefore, two additional parameters were calculated using the subject mean ensemble curves.

The first parameter was the mean absolute value of the ensemble relative phase curve values (MARP). This parameter was calculated by averaging the absolute values of the ensemble curve points for the designated periods (PL and S). 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 relative phase curve points for the designated periods (PL and S). Functionally, a low DP value indicates a more stable (less variable) relationship between the two segments’ actions for this condition and for this given subject. Lastly, group means were also calculated for MARP and DP for each segmental relationship, for each period, and for each condition.

Finally, the obstacle clearance height (CH) was also identified for each trial. The CH was calculated in centimeters and as the difference between the y-coordinates of the metatarsal and the obstacle markers, at the instance which the x-coordinates of the two markers are approximately equal. For the no obstacle condition, a marker on the ground (placed at the same location as the obstacle) was used in a similar manner to calculate CH. The mean CH value was calculated for each subject-condition. Group means were also calculated for each condition.

### 2.5. Statistical analysis

One-way repeated measures ANOVAs (obstacle height with subjects as the repeated factor) were performed on the subject means for MARP, DP and CH. For MARP and DP, statistical analysis was performed for each coordinate relationship (foot–leg and leg–thigh) and for each period (PL and S). In tests that resulted in a significant F-ratio \((P < 0.05)\), a Tukey multiple comparison test was used to identify the location of the significant differences.

### 3. Results

The group results are presented in Table 1. The foot–leg (F–L) MARP group results were statistically significant during both the PL \((F(6,54) = 16.26, P < 0.001)\) and S periods \((F(6,54) = 7.92, P < 0.001)\). For the PL F–L MARP, the post-hoc analysis indicated a large number of significant differences (Table 1). From the post-hoc results, it can be observed that significant differences began with the 15% obstacle condition. In addition, it can be seen that the F–L MARP values
between the 10 and 12.5% obstacle conditions displayed a small difference (0.77°). A similar observation can be made between the 15 and 17.5% obstacle conditions (1.23° difference). The greatest difference between subsequent conditions can be observed between the 12.5 and 15% obstacle conditions (12.44°). Furthermore, the 22.5% obstacle condition showed the highest F−L MARP value, while the lowest value was presented at the no obstacle condition. In general, there was an increase in F−L MARP values with increases in obstacle height. This indicated that the increased obstacle height resulted in more out-of-phase segmental relationship at the ankle joint during the PL period.

The post-hoc analysis for the S F−L MARP values also revealed several significant differences (Table 1). It was observed that significant differences began with the 15% obstacle condition. In addition, it was seen that the higher the obstacle, the larger the S F−L MARP values. This indicated that the increased obstacle height resulted in more out-of-phase segmental relationship at the ankle joint during the S period. The PL and S F−L MARP values showed that the no obstacle condition had the smallest standard deviation compared to all other conditions. The low standard deviation for the no obstacle condition suggested little variability or a similar response between subjects for each specific condition.

The L−T MARP group results were statistically significant during both the PL ($F(6,54) = 5.46, P < 0.001$) and S periods ($F(6,54) = 3.68, P < 0.01$). For the PL, the post-hoc analysis indicated a large number of significant differences (Table 1). It was observed that the introduction of the obstacle resulted in an immediate and significant increase (12.44°; between no obstacle and 10%). However, subsequent to this increase, the L−T MARP values progressively decreased almost to the level of the no obstacle condition. For the S period, the post-hoc analysis also revealed several significant differences. The no obstacle, 10 and 17.5% conditions were significantly different from the 22.5% obstacle condition. The 22.5% had the smallest value of all conditions indicating a more in-phase segmental relationship at the knee joint for this condition.

The PL DP group results were statistically significant for both F−L ($F(6,54) = 9.32, P < 0.001$) and L−T ($F(6,54) = 3.55, P < 0.01$). For the F−L DP, the post-hoc analysis revealed a large number of significant differences (Table 1). It is interesting to notice that again significant differences began with the 15% obstacle condition. It should also be noted that the F−L DP values increased with the increasing obstacle height. This may indicate instability and/or change in behavior. For the L−T DP, the post-hoc analysis revealed three comparisons as significant (Table 1). The largest value was associated with the no obstacle condition, which was opposite of what was found at the F−L DP. Furthermore, all obstacle conditions displayed fairly similar values for the L−T DP indicating a more stable relationship between the two segments at the knee joint for this condition.

The S DP group results were statistically significant only for the L−T ($F(6,54) = 2.94; P < 0.05$). The post-hoc analysis revealed two comparisons as significant (Table 1). The no obstacle and the 10% conditions were
significantly different from the 22.5% obstacle condition. The 22.5% had the largest value of all conditions indicating a possible instability and/or change in behavior in this condition.

The CH group results were also statistically different ($F(6,54) = 9.093; P < 0.001$). The post-hoc analysis revealed a large number of significant differences (Table 1). It was observed that the introduction of the obstacle resulted in an immediate and significant increase (7.81 cm; between no obstacle and 10%). However, subsequent to this increase, the CH values progressively decreased almost to the level of the no obstacle condition.

The group mean ensemble F–L relative phase curves for the PL period are displayed in Fig. 2. It can be observed that in the first 90% of the PL period all curves had a similar configuration. The no obstacle and the 10 and 12.5% obstacle conditions were very close to the zero line indicating a more in-phase segmental relationship. The higher obstacles had higher negative values indicating that the leg was leading the foot. After the first 90% of the PL period and as it was indicated by the positive values, all obstacle conditions changed by having the foot leading the leg to prepare for foot strike. The relative phase values increased quickly for all obstacle conditions 15% and above, ending PL more out-of-phase (values away from 0°). However, the no obstacle condition ended the PL period in the opposite fashion and at 0° (an in-phase segmental relationship). The 10 and 12.5% obstacle conditions also ended the PL period in-phase.

The group mean ensemble L–T relative phase curves for the PL period are presented in Fig. 3. For all conditions, relative phase began around 70°. However, all conditions ended PL more in-phase and with negative values less than −50°. The positive values indicated that the leg was leading the thigh during most of the PL period. In late PL, the thigh took the lead. All curves showed similar configurations. Only the no obstacle condition revealed differences but just in values and not in configuration.

The group mean ensemble F–L relative phase curves for the S period are displayed in Fig. 4. For the no obstacle, 10 and 12.5% conditions, relative phase began around 0° indicating an in-phase relationship. This result indicated that when a low or no obstacle was present, both segments moved in a similar fashion after foot contact. That was not the case for the obstacle conditions higher than 15%, where relative phase values were closer to 80° and more out-of-phase. In these conditions the foot was clearly leading the leg in early S. Around 30% into the S period, all curves merged together and continued with a similar configuration to toe off. Later in the S period, the negative values indicated that relationship between the two segments was reversed and the leg was leading the foot.

The group mean ensemble L–T relative phase curves for the S period are presented in Fig. 5. For all conditions, the L–T relative phase began with negative values that indicated that the thigh was leading the leg. Toward mid-S the two segments were in-phase (0°) but during late S the relationship was reversed with the leg leading. This was indicated by the positive values. It
can be observed that all conditions had a similar configuration for the L–T segmental relationship, or in other words the relationship between the leg and thigh remained the same during the S period.

4. Discussion

The purpose of this paper was to investigate the different strategies used following obstacle clearance during running. To accomplish this purpose, subjects ran over obstacles of various heights and the analysis was based upon the DST. Thus, based on the tenets of DST, a specific procedure was followed in this investigation [2,28,29]. In this procedure, the first goal was to identify appropriate variables that characterize the movement patterns under study. These variables are called order parameters. The relative phase of limb segments was selected within the same leg (intralimb coordination) as the appropriate order parameter. The literature [29–31] supports such a selection, because the use of relative phase incorporates both the periodic and the coupling motion of the segments involved.

Upon completing this goal, the next step was to observe the movement patterns to identify specific coordinated motor patterns or attractors. To accomplish this step, another variable was identified that can move the system through its collective states. This variable is called the control parameter and when it reaches a critical threshold, a transition to a new attractor will occur. The changes of the control parameter are reflected upon the order parameter and therefore reveal the dynamics of the attractors. In the present study, the height of an obstacle that a runner had to overcome was selected as a possible control parameter. This proposal was driven by the premise that a behavioral change would occur with increases in obstacle height. Subsequently, the order parameters were examined for any changes caused by the scaling up of the control parameter.

The results revealed such changes both statistically and graphically. The PL and S F–L MARP significantly increased. It was very interesting that significant differences in both periods and in comparison to the no obstacle, began at the 15% obstacle condition. Furthermore, the greatest increase in PL F–L MARP and in adjacent conditions occurred between the 12.5 and 15% obstacle conditions. A large difference between these two conditions was also found in the S F–L MARP. In addition, Figs. 2 and 4 revealed that in late PL and in early S the geometric configuration of the curves changed between the same two obstacle conditions. This change was displayed not only in terms of values but in the reversing of the curves’ concavity (Fig. 4). Similar changes were found by Kelso [3] in the experiment described in the introduction of this paper. Therefore, it is possible that the 15% obstacle condition is a critical threshold for the control parameter where a behavioral change can occur for the F–L segmental relationship. The fact that the F–L MARP values significantly increased in both periods with obstacle height indicated that the foot and the leg are moving...
out-of-phase or away from each other in the higher obstacles. Such an action is translated as increased plantarflexion of the ankle. Therefore, it can be suggested that in the higher obstacle conditions the foot contacted the ground in a plantarflexed orientation (a forefoot strike), while in the small obstacle conditions (10 and 12.5%) the foot retained the usual dorsiflexed ground contact (heel strike).

These results are in agreement with Scholten et al. [21], where it was also suggested that the 15% obstacle height may be a critical threshold. The authors [21], using ground reaction force data, indicated that at this height the foot strike pattern of the leading leg during landing after clearing an obstacle, changed from a heel strike to a forefoot strike. Landing after a high jump as in a basketball rebound has also been shown to exhibit a different foot strike pattern than landing after the running airborne period [17]. Since overcoming high obstacles can actually force an individual to jump and not run over them, it seemed logical to connect the control parameter with such a behavioral change. Therefore, two different attractors were observed before and after the 15% obstacle height which were probably two different types of landing, a heel strike and a forefoot strike.

This behavioral transition might be a preventive mechanism. Clearing an obstacle has been associated with increased impact forces [11]. However, as Co et al. [32] and Oakley and Pratt [33] have shown, forefoot strike runners can produce lower transient forces than heel strikers. It has also been shown that increased impact forces during initial contact with the ground can deform the heel pad [34]. The deformation of the fatty heel tissue is proportional to the force acting on the heel. Thus, by jumping over the obstacles and landing first on the toes might helped the subjects to decrease the stress of the heel. Furthermore, attenuating the increased impact forces could be accomplished by enlarging the contact area and by incorporating additional structures. Thus, the forefoot strike pattern might increase the involvement of other foot structures and especially of the ankle plantarflexors in shock absorption.

A parallel explanation for the behavioral transition at the ankle may be related to the fact that speed was controlled in this study. In general, an obstacle can have a decreasing effect on the running speed. This can be clearly seen in the record times between track and field events of the same distance (i.e. 400 m) which are performed with or without obstacles. Since in the present study the subjects had to maintain the same speed, they may have used a sprinting mechanism [16]. Sprinters run with a forefoot strike pattern to achieve maximum velocity. One of the primary speed mechanisms is produced by the loading effect on the calcaneal tendon. This type of strategy allows increases in speed. Therefore, as obstacle height increased, subjects changed to a forefoot strike not only to allow for prevention and better shock absorption, but perhaps also to minimize the effect of the obstacle on their speed.

Based on the tenets of DST, just prior to the transition to another attractor, greater instability is observed in the order parameter [2,28,29]. After the transition is complete, the system becomes stable again. Thus, when the system is away from transition points and especially
under a preferred behavioral state, it is very stable. In the present study, attractor stability was measured by DP which described the variability of the relative phase. The F–L DP values for both S and PL increased with obstacle height (although non-significant for the S period) indicating instability and probably lack of coordination at the ankle joint. This result supported the concept that increased instability would be present when the scaling up of the control parameter pushes the system to a new attractor. Furthermore, the fact that the smaller F–L DP values for both periods were present at the no obstacle condition supported the DST notion that when the system is under normal preferred conditions (running with no obstacle) it would be highly stable.

However, the 15% obstacle condition did not have the highest F–L DP values, and these values continue to increase with the increased obstacle height. This result is contradictory to the premise that greater instability will be observed just prior to the transition to another attractor and then the system will become stable again. A possible explanation could be that not all subjects changed at the same height. Differential responses between subjects were revealed in terms of an earlier or later transition. This explanation is also supported by the F–L MARP standard deviations values, which increased with increases in obstacle height. These results underlined the importance of individual variability as Dufek et al. [17,35] have previously suggested.

It should be noted that just the introduction of the obstacle had an impact on the results. In Figs. 2 and 3, one can see that the no obstacle condition is different from all the other conditions for large portions of both the S and the PL periods. These differences are more evident at the knee joint (Fig. 3). This observation is also supported statistically in the L–T MARP and DP for the PL period. The introduction of the obstacle generated a more out-of-phase response for the PL L–T MARP which can be translated into increased extension. This response may be again related with increased impact forces. By approaching the ground in a more extended configuration, a greater degree of flexion is allowed during the S period for increased shock absorption. This conclusion is supported by the significant decreases and the more in-phase response observed for the S L–T MARP values. These decreases can be translated as increased flexion during the S period.

The analysis of the CH also revealed that the introduction of the obstacle had an impact on the results. By examining Figs. 2 and 3 and especially the beginning of the curves, it can be observed that the changes in CH are associated more with the knee joint. It can be seen that the higher the obstacle, the more in-phase were the L–T relative phase curves in their start. This result is in agreement with the literature [36,37] where it was indicated that the knee is an important joint for obstacle clearance during walking. Furthermore, the fact that the CH values decreased as the obstacle became higher and after the 10% obstacle condition, it may be due to the less room available for obstacle clearance. Thus, the subjects had to cross closer to the obstacle because hip and knee flexion were almost exhausted.

After obstacle clearance and during PL, L–T DP significantly decreased which may suggest that the system actually became more stable at the knee. This
increased stability may be a knee strategy that is robustly used for obstacle clearance. This explanation can be supported from studies conducted in obstacle clearance during walking [36,37]. Furthermore, an alternative explanation can be derived if the early stages of the acquisition of a movement skill are considered [1,38]. During these stages, the coordination problem is reduced by decreasing the degrees of freedom. This can be done by stereotyping segmental actions and decreasing allowable movement of the joints. Thus, decreasing the available degrees of freedom and becomes more stable at the knee. In addition, the knee joint is a major shock absorber. Thus, decreasing the degrees of freedom may also be attributed to an effort to cope with the new task, the system freezes degrees of freedom and becomes more stable at the knee. In addition, the knee joint is a major shock absorber. Thus, decreasing the available degrees of freedom may also be attributed to an effort to handle the increased impact with the ground after clearing an obstacle.

On the contrary, the S L–T DP increased significantly for the highest obstacle condition. This phenomenon can be explained as an increased instability which can be the result of extremely high impact forces at this level. It is possible that the system retained a stable relationship until this condition but then it was unable to maintain its stability. It can be speculated that such a response may be indicative of an unfolding of degrees of freedom and a potential development of a new attractor or behavioral state at this level.

Previously, angle–angle diagrams have been used to depict the organization of the multiple degrees of freedom needed to complete one running gait cycle [12,39]. However, quantitatively understanding the control mechanisms cannot be achieved with this methodology alone. As Burgess-Limerick et al. [40] discussed, the angle–angle diagrams lack the ability to effectively quantify inter-joint coordination. The DST and the tools provided under this theoretical framework cannot only be used to describe movement, but can provide a window into control processes [2–5,29,31,40]. The usage of relative phase allows the incorporation of both angular displacement and velocity to examine coordination and movement. This approach is advantageous since there is evidence that receptors exist within the muscles and tendons for controlling both displacement and velocity [27].

In conclusion, introducing an obstacle and increasing the obstacle height elicited behavioral changes. The changes were different for the interacting segments at the ankle and at the knee. While the foot and the leg became more independent in their actions, the leg and the thigh strengthened their already stable relationship. The 15% obstacle height seems to be a critical height for the observed changes. The DST might be an effective approach to examine questions related with coordination of locomotion.

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