12-2005

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Running head: Joint kinetics during obstacle running

Abstract

When running over obstacles of increasing height, heelstrike runners switch to a forefoot landing pattern once a critical obstacle height is reached. The primary purpose of this study was to determine whether ankle or knee joint kinetic variables trigger the gait change from a heelstrike to a forefoot striking pattern as obstacle height increases. Ten subjects were filmed from the sagittal plane as they ran at their preferred running speed over a force platform during six obstacle height conditions ranging from 10% to 22.5% of standing height, as well as an additional baseline condition with no obstacle (0%). An inverse dynamics approach was utilized to calculate ankle and knee joint kinetics at each condition. Although no variables were found which met all of the criteria necessary to be considered a determinant of the gait transition, there were variables which distinguished between a heelstrike and forefoot strike landing pattern as obstacle height increased. Differences in joint kinetics did not occur until a height was reached at which the landing strategy changed from a heelstrike to a forefoot landing pattern. Most differences occurred at the ankle joint, at which there was a greater maximum plantar flexor moment and a greater amount of energy absorbed when obstacles of sufficient height to require a forefoot landing pattern were negotiated.

Keywords: joint moments, joint powers, gait transitions, running

Introduction

A gait has been defined as "a pattern of locomotion characteristic of a limited range of speeds described by quantities of which one or more change discontinuously at transitions to other gaits." (Alexander, 1989, p. 1200). Humans primarily utilize two different gaits during terrestrial locomotion, walking and running, but variations of these patterns, such as heel walking or forefoot running, could be considered to be "gaits" from this definition since several kinematic quantities vary discontinuously when these patterns are altered. Although gait transitions occur most commonly as a consequence of changes in the horizontal speed of locomotion, it may also be possible to induce some gait transitions by changing the vertical component of speed. As an example, at slow to moderate speeds of running on level ground, most runners are heelstrikers, making first ground contact with the posterior third of the foot (Bates et al., 1978; Nilsson & Thorstensson, 1989). If a heelstrike runner is forced to run over obstacles of increasing height, thereby increasing the downward component of his/her landing velocity without increasing the horizontal component, a critical height is eventually reached at which point the runner chooses to switch to a forefoot landing pattern (Stergiou et al., 2001).

The walk to run gait transition for humans occurs spontaneously over a narrow range of speeds, reported to be between 1.89 $m \cdot s^{-1}$ and 2.16 $m \cdot s^{-1}$ (Beuter & Lefebvre, 1988; Brisswalter & Mottet, 1996; Diedrich & Warren, 1995, 1998; Hreljac, 1993, 1995a, 1995b; Kram et al., 1997; Mercier et al., 1994; Minetti et al., 1994; Thorstensson & Roberthson, 1987; Turvey et al., 1999), which is considerably less than a person's maximum walking speed of approximately 3.0 $m \cdot s^{-1}$ (Alexander, 1989). It is likely that the switch from a heelstrike to a forefoot striking pattern as subjects run over obstacles of increasing height would also occur at heights lower than the maximum height necessary to make this change. Since it has been suggested (Beuter & Lefebvre, 1988; Hreljac, 1995a; Hreljac et al., 2001; Minetti et al., 1994) that there are mechanical triggers that induce the walk to run gait transition, it is possible that there also exists a mechanical trigger that induces the heelstrike to forefoot change in gait pattern when subjects run over obstacles. Determining the nature of the trigger for this gait pattern change may lead to a better understanding of spontaneous gait transitions in general.

Among other things, foot landing patterns have a profound effect on lower extremity joint kinetics. Novacheck (1995) reported major differences between running and sprinting in the magnitude and time history of lower extremity joint moments and powers, where sprinting was primarily differentiated from running by the presence of an initial forefoot contact. Although some of the differences noted between running and sprinting may have been attributed to speed variations, landing pattern differences were likely a major factor. Even when speed has been held constant, joint kinetics appear to differ between a heelstrike landing and a forefoot landing. Harrison et al. (1988) demonstrated that joint reaction forces (particularly at the knee) differed considerably between a group of heelstrike runners and a group of forefoot strikers running at the same speed. Hamill et al. (2000) found that energy absorption is superior when utilizing a forefoot landing pattern compared to a heelstrike pattern when running at comparable speeds. During the propulsive phase of running, these researchers (Hamill et al., 2000) reported that the ankle is a better energy generator following a forefoot landing than following a heelstrike landing, while energy generation contributions from the knee did not vary considerably between landing patterns.

As landing pattern changes when running over obstacles of increasing height, it is inevitable that modifications in the joint kinetic patterns of the ankle and knee would be necessary, although it is not clear whether these changes are determinants of the gait change from a heelstrike to a forefoot striking pattern, or whether they could be used to distinguish between the landing patterns. The primary purpose of this study was to compare selective ankle and knee joint kinetic variables between level running at a self selected pace and running over obstacles at heights up to the transition height (height at which landing pattern changes from a heelstrike to a forefoot striking pattern). It was hypothesized that one or more of these joint kinetic variables would meet the criteria to be considered a determinant of the gait change from a heelstrike to a forefoot striking pattern as obstacle height increases. A secondary purpose was to determine whether the observed differences in joint kinetics are due to increases in obstacle height or to changes in landing pattern.

In previous studies related to the walk-run gait transition (Beuter & Lefebvre, 1988; Hreljac, 1995a, 1995b; Hreljac et al., 2001; Mercier, 1994), one criterion established to identify whether a variable was a determinant of the gait transition was that the variable must exhibit an abrupt change in its value as gait is changed. This is consistent with the definition of a gait (Alexander, 1989). In addition to merely changing abruptly, the direction of the change must be considered. If the value of a variable increases as speed increases, the variable must suddenly decrease in value when gait is changed. Logically, this could be a mechanism to reduce injury potential or local fatigue. A similar set of criteria has been used in the current study to establish whether variables tested are determinants of the transition from a heelstrike to a forefoot landing pattern as obstacle height increases.

Methods

Participants in this investigation were ten healthy male (n =4) and female (n =6) recreational runners (age = 23.5 ± 2.5 y; body mass = 67.5 ± 15.3 kg; height = 173.9 ± 9.3 cm), each of whom signed a university approved informed consent form reiterating the basic procedures and intent of the study, as well as warning of any potential risks as a result of participation. Prior to the experimental session, potential subjects were observed while running at their preferred speed. Only subjects who exhibited a heelstrike landing pattern at this speed were admitted to the study. During the experimental session, subjects wore their regular running shoes to assure normal performance.

The testing area consisted of a 40 x 0.6 m runway, equipped with a floor mounted force platform (Kistler Model 9281-B11, Amherst, NY) connected to a signal conditioner/amplifier (Kistler Model 9807, Amherst, NY), located 25 m from the start of the runway. Two sets of infrared photocell timing lights, connected to a digital timer, located three meters apart, and centered at the force platform, were utilized to monitor running speed.

For a warmup and accommodation period, subjects ran through the testing area at their preferred speed as often as desired without concern for stepping on the force platform. This accommodation period was also utilized to accurately establish each subject's preferred running speed and stride length.

For all test trials, subjects ran at their established preferred running speed during six obstacle height conditions (10%, 12.5%, 15%, 17.5%, 20%, and 22.5% of the subject's standing height), as well as an additional baseline condition with no obstacle (0%). The obstacle was positioned directly in front of the force platform so that the leading (right) foot would clear the obstacle and then contact the force platform completely. Obstacles were made of light weight balsa wood. When a subject stepped on or hit an obstacle, the obstacle was destroyed to minimize the risk of the subject tripping and/or falling. The heights of the obstacles were established based upon pilot work and previous literature (Stergiou et al., 1999). In order to reduce the chance of subjects changing stride length when clearing the obstacle, a marker was placed one step before the force platform to identify left foot landing position. Subjects were instructed to hit this marker with their left foot prior to clearing the obstacle and landing on the force platform with their right leg. Ten successful trials were performed for each of the randomly ordered obstacle height conditions. A trial was considered successful only if the obstacle was satisfactorily negotiated, the running speed was within ± 5% of the subject's established preferred running speed, and the landing foot completely contacted the force platform.

The motion of five markers, placed on the hip (greater trochanter), knee (estimated knee joint center), ankle (lateral malleolus), heel (calcaneus), and toe (head of fifth metatarsal) of the landing leg were recorded in the sagittal plane with a single video camera (180 Hz) for at least 10 frames prior to heelstrike and after toeoff of each trial. Two-dimensional (2-D) kinematic data were synchronized with ground reaction force (GRF) data (900 Hz) collected in the horizontal (F_x) and vertical (F_y) directions.

Raw 2-D coordinate data were smoothed using a fourth order, zero lag, Butterworth filter, with optimal cutoff frequencies uniquely chosen for each coordinate of each marker using a residual method (Wells & Winter, 1980). Ankle and knee joint velocities were calculated from the smoothed data using a finite difference method. Joint reaction forces and moments were determined using a standard inverse dynamics approach, applying the de Leva (1996) model for necessary anthropometric data. Ankle and knee joint powers were calculated as the product of the respective joint moment and angular velocity. Prior to analysis, all variables were normalized by dividing by body mass.

When running with a heelstrike landing pattern, the ankle naturally demonstrates an initial plantar flexion phase at ground contact (Ardigo et al., 1995). Since this initial plantar flexion phase is not present during a forefoot landing, the initial portion of ankle angular velocity graphs were utilized to determine the type of landing pattern during a trial (Figure 1). The height at which no initial plantar flexion occurred was defined as the transition height (TH) between a heelstrike (HS) and a forefoot (FF) landing pattern. Inevitably, there were subjects for whom conditions existed which contained trials exhibiting both HS and FF landing patterns. The TH was more specifically defined as the height at which a majority of trials exhibited a FF landing pattern, as illustrated in Figure 1. If conditions for a subject contained trials with both landing patterns, only trials of the landing pattern exhibited by the majority of trials were utilized in the subsequent analyses.

Dependent variables analyzed at the ankle included: maximum plantar flexion moment (AM_{PF}), maximum power absorption (AP_{ABS}), and maximum power generation (AP_{GEN}). At the knee, dependent variables analyzed included: maximum extensor moment (KM_{EXT}), maximum initial flexor moment (KM_{FLEX}), maximum power absorption (KP_{ABS}), and maximum power generation (KP_{GEN}). The dorsiflexor moment was not analyzed since a dorsiflexor moment did not exist in several conditions. All dependent variables were compared between level running (H0), the next lower condition to the transition height (H1), and TH using a repeated measures MANOVA ($p = 0.05$). Helmert contrasts were used to compare the means of dependent variables between each pair of obstacle heights.

Results

The average transition height of all subjects was 15.0 ± 2.5% of standing height, similar to that reported by Stergiou et al. (2001). Data from three subjects whose transition height was 10% of standing height were not utilized in comparisons involving the H1 condition.

For illustrative purposes, ensemble average graphs of ankle and knee joint moments over the complete stance time during H0, H1, and TH are illustrated in Figures 2a and 2b. Ensemble average curves of ankle and knee joint power curves are shown in Figures 3a and 3b.

At the ankle, AM_{PF} and AP_{ABS} were significantly greater at the TH than at the H0 and H1 conditions (Table 1). No difference in AP_{GEN} occurred between conditions. None of the variables measured at the ankle were significantly different between the H0 and H1 conditions.

At the knee, only KM_{FLEX} was significantly greater at TH than at H0 and H1 conditions (Table 1). None of the variables measured at the knee differed significantly between the H0 and H1 conditions. Since the representative graphs (Figures 2 and 3) are ensemble average curves, some of the variable values shown in Table 1 do not correspond exactly to the values illustrated in these figures.

Discussion

None of the variables tested during this study met all of the criteria necessary to be considered a determinant of the gait transition from a heelstrike to a forefoot strike pattern as obstacle height increased since no significant differences were found in any of the variables between the H0 (level) and the H1conditions. There were, however, variables which distinguished between the heelstrike and forefoot strike landing patterns, as noted by the differences between the TH (transition height) condition, in which a forefoot landing was exhibited, and the two other conditions in which a heelstrike landing was exhibited.

It has been suggested (Nigg, 1985) that landing velocity and foot position at contact are two of the primary factors that affect the magnitude and pattern of initial forces and moments on the lower extremity joints during running. In both the H0 and H1 conditions, subjects contacted the ground with a heelstrike landing pattern. It could be assumed, however, that the landing velocity (both magnitude and direction) differed between these conditions since the height above the ground and the angle of descent differed between these conditions. Despite the landing velocity differences between the H0 and H1 conditions, there were only minor differences noted in the time histories of ankle and knee joint moments and powers between these conditions. On the other hand, the landing pattern during the TH condition was different than during the H0 and H1 conditions (FF pattern versus HS pattern), but landing velocity would have been similar between the TH and the H1 conditions since the heights dropped were similar.

There were fairly large differences between the TH condition and both the H0 and H1 conditions in the time histories of ankle and knee joint moments and powers (Figures 2 and 3) suggesting that it is primarily the landing pattern which produced the differences in joint moments and powers between level running and the transition height condition.

A greater peak ankle plantar flexion moment was observed during the TH condition than at conditions exhibiting a HS landing pattern. The peak plantar flexion moment occurred at about midstance, although this moment appeared to be greater in the TH condition than during the H0 or H1 conditions throughout the first half of the stance phase (Figure 2a), approximately corresponding to the time period during which the ankle was dorsiflexing (Figure 1). The plantar flexors, acting eccentrically during this time period, may have been storing elastic energy. When jumping following a FF landing, subjects also produce greater plantar flexion moments than following a HS landing (Kovács et al., 1999). During level running, Komi (1990) demonstrated that a greater tendon force is developed using a FF landing than a HS landing pattern when running at comparable speeds. When storing large amounts of elastic energy, as could occur when using a FF landing pattern, there may be performance benefits as the stored energy is released, although these benefits are likely to come at an increased metabolic energy cost since only a percentage of the stored energy may be recovered. This would make a FF landing the preferred pattern for short duration events in which large forces are the most important performance criterion such as during jumping or sprinting, while a HS landing pattern may be preferred when metabolic energy cost is important, such as during longer distance running.

In all landing conditions, a relatively small initial knee flexion moment was observed within the first 10% of stance (Figure 2b). The peak knee flexion moment was greater during the TH condition than during the H0 and H1 conditions. It has been suggested (Devita & Skelley, 1992) that this initial knee flexion moment is due to tension produced in the hamstring muscles to reduce hip flexion velocity. Although hip and knee angles were not analyzed during this study, it is logical to assume that in the TH condition, in which a FF landing pattern was utilized, all lower extremity joints would be less flexed at foot contact than when using a HS landing pattern, possibly leading to an overall greater flexion velocity in all lower extremity joints during the initial stance period when a FF landing pattern was evident, requiring greater eccentric contractions to slow the flexion. It should be noted, however, that there was considerable within and between subject variability in this variable. There were no differences reported in the initial knee flexion moment between running and sprinting (Novacheck, 1995), nor between a FF and a HS landing during a jump (Kovács et al., 1999).

When subjects switched to a FF landing pattern at the transition height, more power was absorbed at the ankle than during the level running condition, illustrating that a FF landing results in a greater amount of negative work initially being done at the ankle than during a HS landing pattern. Similar results have been reported in both running and jumping. Hamill et al. (2000) noted greater energy absorption at the ankle when subjects used a FF landing pattern compared to the same subjects using a HS landing pattern when running at a speed of 3.5 $m \cdot s^{-1}$. In a drop jump task, Kovács et al. (1999) reported that power absorption at the ankle was considerably greater when subjects landed using a FF landing pattern compared to a HS landing pattern. At relatively low running speeds on level ground, and while running over low obstacles, energy absorption may not be an important consideration for injury prevention, making a HS landing more desirable during these conditions. When running speed or obstacle height reach a critical level, increasing energy absorption is likely to become an important factor in injury prevention.

At the knee, power absorption and generation did not differ significantly between conditions. The knee, however, appeared to contribute a greater relative proportion of the overall power absorption during the HS landings of the H0 and H1 conditions than during the FF landing of the TH condition. In the TH condition, the relative contribution of the knee and ankle remained approximately constant. Hamill et al. (2000) also concluded that there is a greater relative contribution to power absorption at the knee than at the ankle following a HS landing when subjects ran a constant speed. In contrast, during a drop jump, Kovács et al. (1999) demonstrated that the ankle is the major contributor to power absorption following a FF landing, while the knee contributes more to power absorption following a HS landing. Unlike constant speed running, Novacheck (1995) concluded that the knee contributes relatively little to power absorption during sprinting (with a FF landing) compared to running with a HS landing pattern. These observations suggest that joint kinetics while running over obstacles with different landing patterns emulate neither jumping nor sprinting, but more closely resemble constant speed running with landings of similar footfall patterns.

Perspective

There does not appear to be a mechanical trigger which could be considered a determinant of the gait transition from a heelstrike to a forefoot strike pattern, although there are variables which distinguish between the heelstrike and forefoot strike landing patterns regardless of the obstacle height. Differences in joint kinetics between level running and running over obstacles of increasing height do not occur until a height is reached at which the landing strategy changes from a HS landing pattern to a FF landing pattern. Most differences appeared to occur at the ankle joint, at which there was a greater plantar flexor moment and a greater amount of energy absorbed when obstacles of sufficient height to require a FF landing pattern were negotiated.

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Table 1. Mean (±1 SD) of variables of interest at each obstacle height condition.

Variable	Condition		
	H0	H1	TH
AM_{PF} ($N \cdot m \cdot kg^{-1}$)	2.74 ± 0.42	2.91 ± 0.27	3.17 ± 0.26**
AP_{ABS} ($W \cdot kg^{-1}$)	8.19 ± 1.98	8.54 ± 2.02	19.09 ± 8.42**
AP_{GEN} ($W \cdot kg^{-1}$)	10.85 ± 2.03	11.68 ± 1.85	12.29 ± 2.29
KM_{EXT} ($N \cdot m \cdot kg^{-1}$)	2.52 ± 0.53	2.55 ± 0.39	2.36 ± 0.35
KM_{FLEX} ($N \cdot m \cdot kg^{-1}$)	0.52 ± 0.19	0.75 ± 0.41	1.09 ± 0.34**
KP_{ABS} ($W \cdot kg^{-1}$)	16.25 ± 3.57	18.88 ± 4.98	16.53 ± 4.89
KP_{GEN} ($W \cdot kg^{-1}$)	4.53 ± 1.23	4.47 ± 0.97	5.07 ± 1.76

** TH > (H0 = H1), $p < 0.05$

Figure Captions

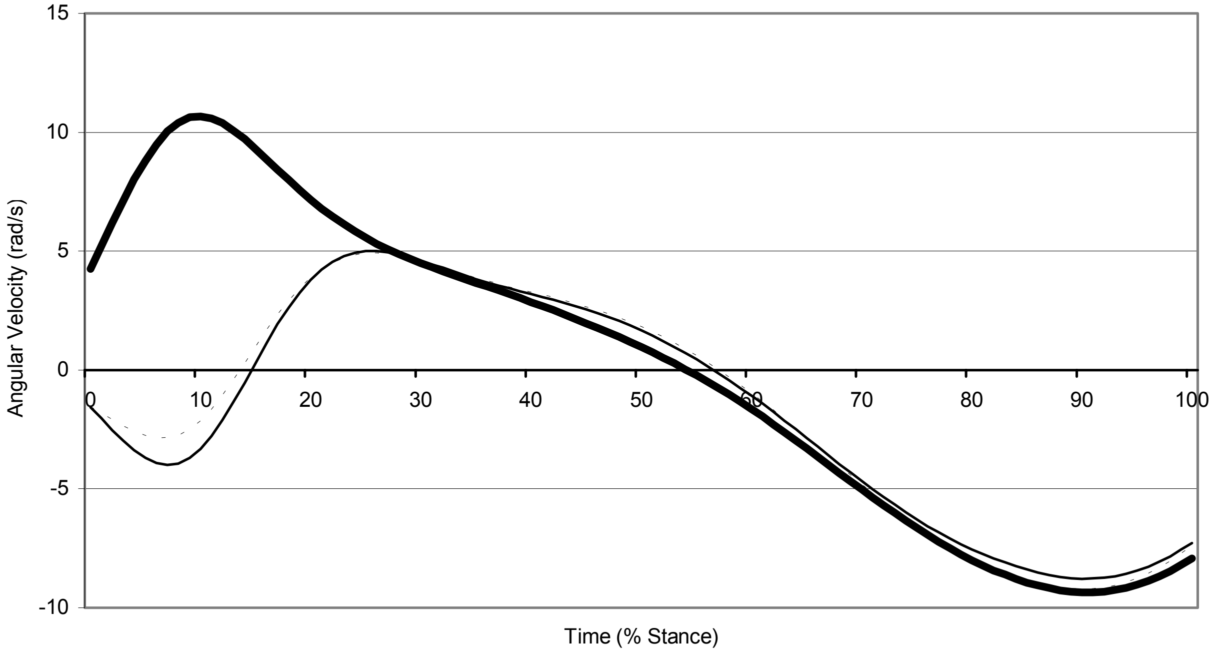
Figure 1. Typical ankle angular velocity vs. time curves during the stance phase of running for the H0 (——), H1 (- - -), and TH (▬▬) conditions. Positive values represent dorsiflexion.

Figure 2a. Ensemble average graphs of ankle joint moment over the complete stance time during the H0 (——), H1 (- - -), and TH (▬▬) conditions. Positive values represent dorsiflexion moments.

Figure 2b. Ensemble average graphs of knee joint moment over the complete stance time during the H0 (——), H1 (- - -), and TH (▬▬) conditions. Positive values represent knee flexion moments.

Figure 3a. Ensemble average graphs of ankle joint power over the complete stance time during the H0 (——), H1 (- - -), and TH (▬▬) conditions.

Figure 3b. Ensemble average graphs of knee joint power over the complete stance time during the H0 (——), H1 (- - -), and TH (▬▬) conditions.



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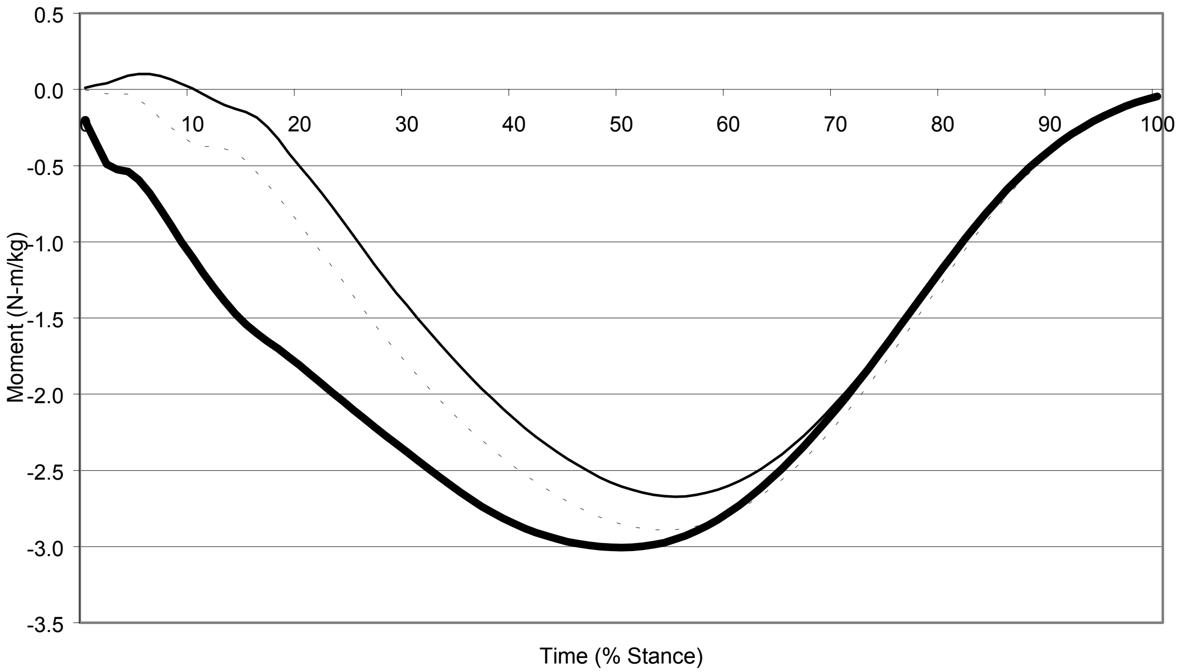
Time (% Stance)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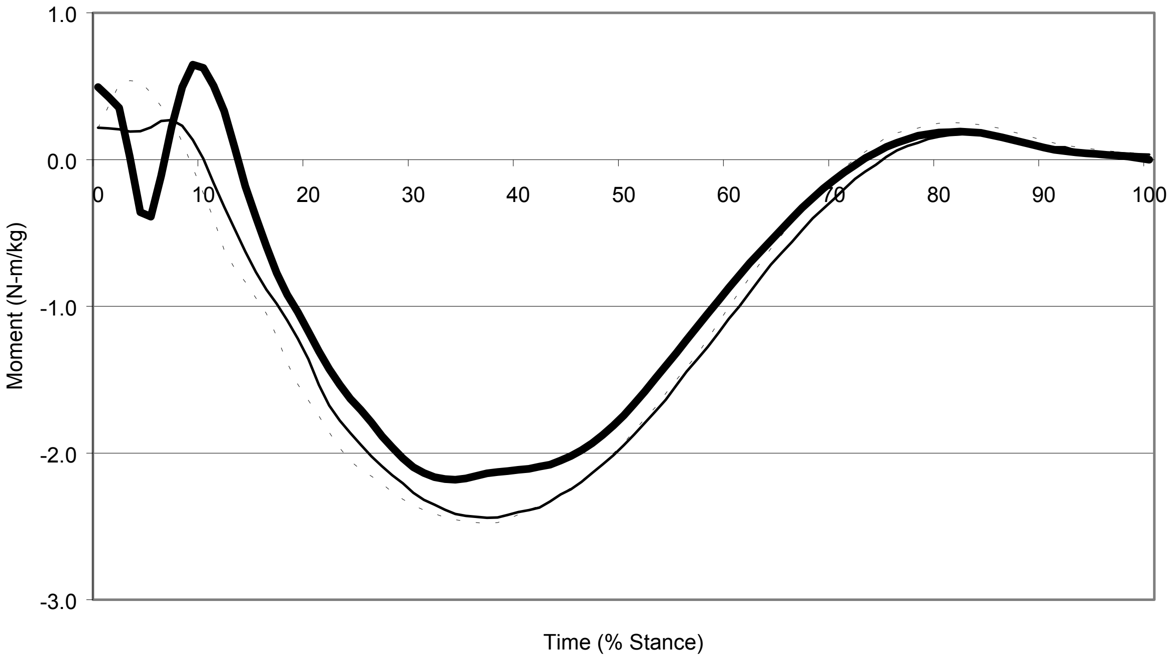
Moment (N-m/kg)
Time (% Stance)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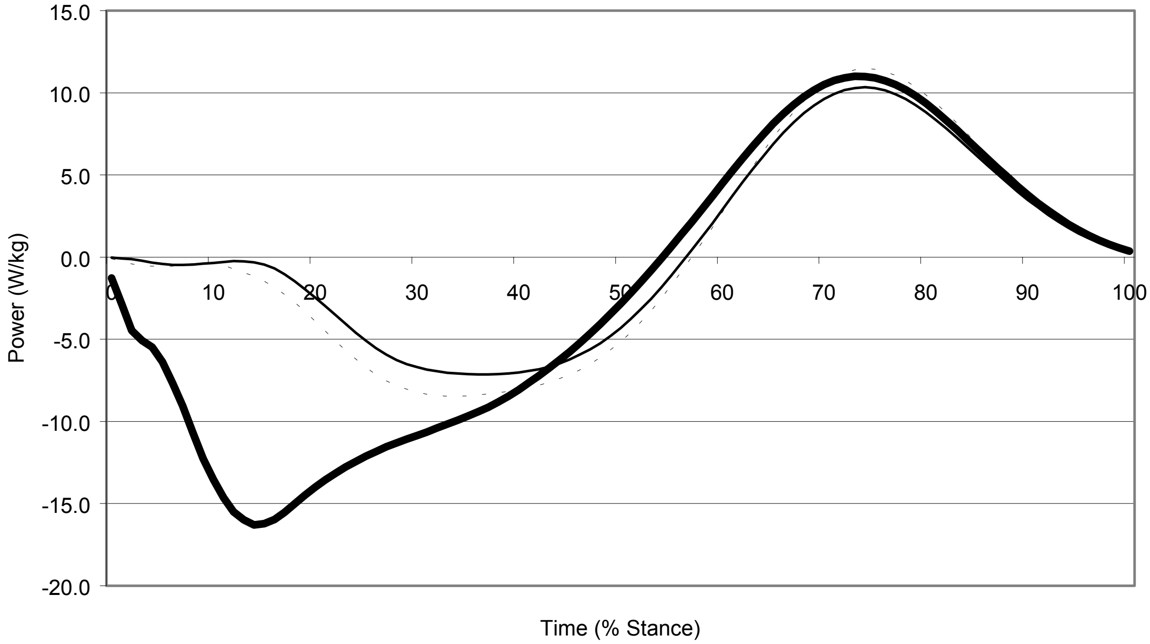
Moment (N-m/kg)
Time (% Stance)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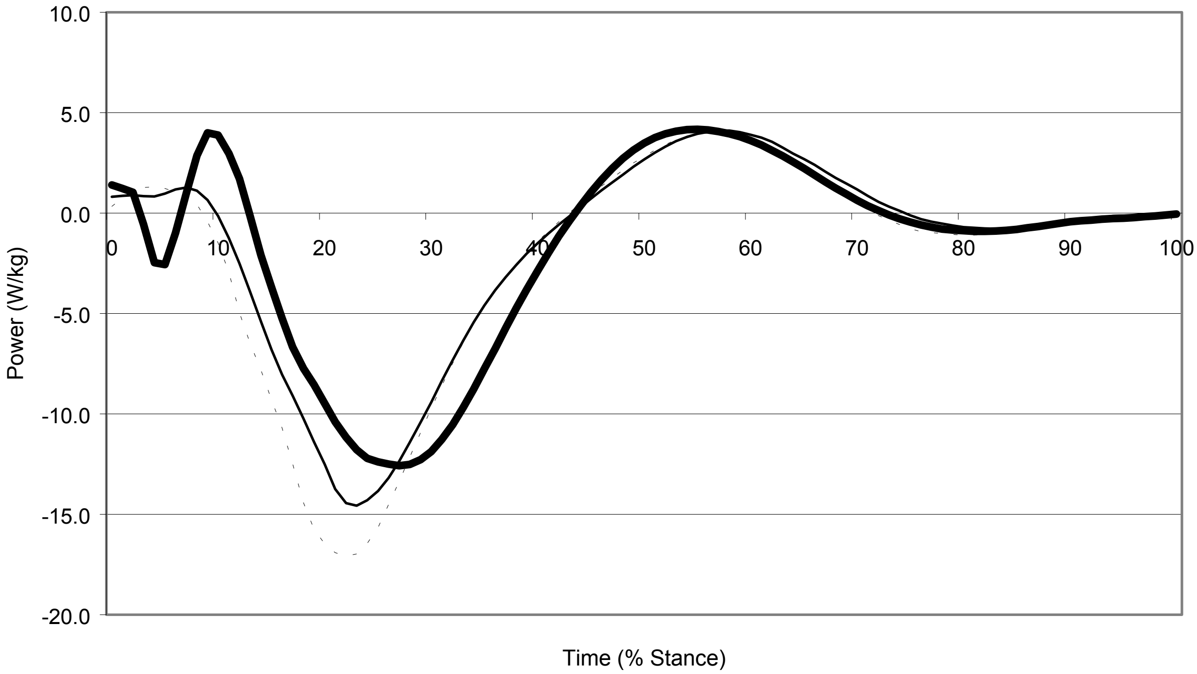
Time (% Stance)



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