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Biomechanics of trailing leg response to slipping - Evidence of interlimb and intralimb coordination

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Abstract

This gait study characterizes the trailing leg's biomechanical response to slips. Twenty-eight healthy participants divided into two age groups (20–33 years and 55–67 years) were asked to walk in two conditions: a known dry floor and a glycerol-contaminated floor expected to be dry, inducing an unexpected slip of the leading foot at heel contact. Four slip-related trailing leg response strategies were identified, ranging from a minimal disruption of the swing phase to a premature (~50 ms after toe off) interruption of the swing phase. Aging effects were minimal. The response of the leading/slipping leg preceded that of the trailing limb. The magnitude of the trailing leg's response was associated with that of the knee in the leading/slipping leg, suggesting interlimb coordination. The corrective moment at the knee of the trailing leg was also correlated with that measured at the hip in the same leg, suggesting intralimb coordination. The specific trailing leg's strategy used in a slip is partially determined by pre-slip walking patterns and early stance slip dynamics.

Keywords

Slips; Falls; Trailing leg; Stepping; Hind leg; Gait; Coordination

1. Introduction

Slip-related postural responses are complex and involve the legs, arms and trunk. These responses can be affected by aging, including sensory systems and strength degradation, slowed reaction time, reduced response magnitude, and lack of coordination [1], [2], [3], [4], [5] and [6]. Slips associated with the greatest risk of falling occur at heel contact (HC) [7]. Shortly after HC, corrective joint moments generated by the leading/slipping leg, namely flexion moment at the knee and extension moment at the hip, slow down the sliding motion of the foot and possibly minimize the vertical descent of the body [6], [8] and [9].

While corrective reactions generated by the leading/slipping leg have been studied [2], [8], [10] and [11], much less is known about the trailing leg's response. Studies using simulated slips perturbation paradigms have shown that an interruption of the swing phase occurs [4],

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Conflict of interest
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[5], [6] and [12]. The results of these studies have paralleled findings related to stepping responses during standing balance perturbations [13], [14], [15], [16] and [17]. Specifically, a stepping response is necessary to recover balance from larger perturbations, creating a stable base of support and preventing body collapse. Additionally, previous studies have underlined the necessity of coordinating bilateral leg responses [6] and [18]. While prior research has certainly contributed to the identification of the trailing leg's reaction as a critical component of the balance recovery response, there is a concern that postural responses to simulated slips may differ from responses to actual slips occurring on contaminated flooring surfaces [19]. Also, there is a lack of precise characterization of the kinetics of the trailing leg's response even in studies using simulated slips.

The purpose of this study was to describe and quantitatively characterize the postural response of the trailing leg in naturally occurring slips in younger and older adults. Interlimb and intralimb coordination were also studied. Additionally, associations between bilateral lower extremity responses and slip severity were examined.

2. Methods

Twenty-eight subjects were recruited in two age groups, a younger group (9 F, 6 M, age: 23.5 ± 3.3 years old, body mass: 66.8 ± 10.4 kg and stature: 170.2 ± 8.3 cm) and an older group (5 F, 8 M, age: 61.1 ± 3.7 years, body mass: 76.5 ± 11.8 kg and stature: 165.8 ± 7.7 cm). Written informed consent, approved by the University of Pittsburgh Institutional Review Board (IRB Approval number 010871), was obtained prior to participation. Exclusionary criteria included clinically significant neurological, orthopedic, cardiovascular or pulmonary abnormalities hindering normal gait and balance.

Subjects wore polyvinyl chloride soled shoes and donned a safety harness. A set of 79 reflective markers were used to track gait kinematics at 120 Hz while walking across an 8.5 m long vinyl tiled walkway [20]. Bilateral ground reaction forces were sampled at 1080 Hz. Subjects practiced walking with the lights in the laboratory dimmed to prevent discerning the possible application of the slippery contaminant on the floor. Participants were instructed to walk as naturally as possible at a self-selected comfortable pace. Prior to each recorded trial, subjects walked to the start of the gait path, faced away from the walkway, and listened to music via headphones for 1 min. The music disguised audible hints of possible contaminant application. At the end of the waiting period, subjects were asked to turn around, to focus on a target placed at eye-level on the far wall, i.e. not look down, and to walk. To ensure natural gait, participants were informed that the first few trials would be non-slippery. Few dry trials were then collected (known dry/baseline condition) ensuring appropriate foot contact. Then, without the participant's knowledge, a diluted glycerol solution (75% glycerol, 25% water) was applied to the leading leg force platform and another gait trial was conducted (unexpected slippery trial).

Joint moments were computed using inverse dynamics analyses [20]. For this study, only sagittal-plane bilateral joint angles and body mass-normalized joint moments generated at the ankle, knee and hip were of interest. These variables were evaluated at HC and toe off (TO), determined based on vertical ground reaction forces. Slip severity was quantified

using the peak sliding (horizontal) velocity (PSV) measured at the heel marker attached to the leading/slipping foot [21]. As described first in Section 3, four trailing leg strategies were identified. To investigate differences in gait characteristics (joint kinetics/kinematics and slip severity) between trailing leg strategies and age groups, the main analyses consisted of regressing each gait variable of interest on strategy, age group and strategy × age group, with statistical significance set at 0.05.

3. Results

3.1. Identification of trailing leg strategies

Trailing leg responses to slips were categorized into four types of strategies termed minimum (MIN), foot-flat (FF), mid-flight (MID), and toe-down (TD) based on the dynamics of the trailing foot; specifically, flight distance, flight duration and orientation at touch down after the initiation of the slip. During the MIN strategy, trailing leg trajectories were similar to normal walking patterns (Fig. 1). For the other three strategies, the swing phase of the trailing leg was interrupted. Specifically, FF responses were typified by the entire shoe sole of the trailing foot contacting the ground either near or slightly behind the leading/slipping foot (Fig. 1). For the MID strategy, the sole of the forefoot contacted the floor (Fig. 1). Ground contact for the MID strategy occurred more rapidly and more posteriorly with respect to the leading/slipping foot compared to the FF strategy. The TD responses were typified by the tip of the forefoot contacting the floor. Floor contact occurred rapidly after TO causing the foot to contact the floor more posteriorly to the slipping foot (Fig. 1) than for the MID strategy. All trailing leg strategies were found in both age groups.

When PSV was regressed on strategy, age group and strategy × age group, only strategy was statistically significant ($p < 0.001$). Specifically, MIN patterns were associated with the least severe slips (PSV = 0.6 ± 0.1 m/s), followed by FF and MID strategies (PSV = 1.4 ± 0.4 m/s) and then TD responses (PSV = 2.0 ± 0.2 m/s).

3.2. Corrective moments generated by the leading/slipping leg response

As reported previously [8], the primary corrective response produced by the leading/slipping leg consisted of a reduced extension moment at the knee, leading to a flexion moment for more extreme slips, followed by increased extensor moment at the hip. A significant difference of about 50 ms occurred between the onsets of the knee and hip response ($p < 0.001$) (Table 1). The correlation between the moment generation rate of the knee and hip in the leading/slipping leg was not statistically significant ($p = 0.11$, $r = 0.41$). To examine the scaling of the response magnitude with slip severity, the generation rate of the knee and hip corrective moments were regressed on PSV, age group and their interaction. Only knee response scaled with slip severity (ppsv < 0.01, R2 = 0.49).

To further understand the coordination between the two legs, the corrective response of the leading/slipping leg was examined as a function of trailing leg strategy type. Corrective moments generated by the leading/slipping leg were identified in all TD and MID events, and in about 50% of the FF responses (hip and knee corrective moments were identified in 5 and 7 out of 10 FF patterns, respectively). In contrast, a corrective leading leg moment

response was identified in only 1 of the 7 MIN slips. The corrective moment onset and generation rate were compared among the four types of trailing leg strategies (Table 1). Only the leading/slipping leg moment rate at the knee was associated with strategy, with the smallest flexion rates noted in MIN events and the largest rates observed in the TD responses. No age group differences were found in either onset or moment rate.

3.3. Corrective moments generated by the trailing leg

Corrective moments in the trailing leg were initiated after the onset of the leading/slipping leg response (Table 1). Specifically, an average delay of 20 ms and 80 ms were noted for the hip ($p < 0.01$) and knee ($p < 0.001$), respectively. The response of the trailing leg consisted of an extensor moment in the hip and a flexor moment in the knee initiated at about the same time, i.e. about 30% into stance (Table 1, Fig. 2). Generation rates of the hip and knee corrective moments were correlated ($p < 0.0001$, $r = 0.76$). Despite this statistically significant correlation, only the knee response scaled with slip severity but this association was relatively weak with no aging-related effects ($p < 0.05$, $R2 = 0.23$).

Corrective moments generated by the trailing leg were identifiable in all TD, MID and FF events, but not in most MIN events. The onset and generation rates of these corrective moments were significantly associated with trailing leg strategy. In general, generation rates were the smallest in MIN responses and increased in FF/MID events (Table 1). The increasing trend of the generation rates with trailing leg strategy (from MIN to MID) did not continue in TD events (Table 1). As for the leading leg, the trailing leg's ankle corrective moments were reduced compared to the knee and hip joints in severe slips (Fig. 2). However, in MIN responses, an increase (relative to normal walking data) in plantarflexion moment was noted between HC of the leading/slipping leg and contralateral TO (Fig. 2E). No age group differences were found in the corrective moments (onsets and generation rates) generated by the trailing leg.

3.4. Potential determinants of the trailing leg strategy

Gait characteristics during normal walking were compared to trailing leg strategy by regressing bilateral joint moments and angles evaluated at contralateral TO on strategy, age group and strategy × age group. This analysis revealed that a reduced extension moment at the hip in the leading leg was associated with a TD strategy (Table 2, $p_{strategy} < 0.01$). In general, there were no statistically significant age effects ($p > 0.05$). To further understand the possible factors that determine the selection of a specific trailing leg strategy, bilateral joint moments and angles, evaluated at contralateral TO in the contaminated trial, were regressed on strategy, age group and their interaction. First, trailing leg strategy was found to be associated with knee moment in the leading/slipping leg and hip extension in the trailing leg (Table 3, $p_{strategy} < 0.01$). Specifically, subjects with MIN responses had the greatest knee extension moment in the leading leg, followed by FF/MID patterns. In contrast, in TD responses, the activity of the flexors in the knee of the leading leg dominated the extensors at contralateral TO. Also, in the trailing leg, the hip flexion moment, responsible for the swing phase, is reduced in TD/MID slip patterns compared to MIN/FF responses (Table 3, $p_{strategy} < 0.05$). Second, the leading leg knee angle at contralateral TO was associated with

trailing leg strategy, with the least flexion noted in TD responses and the most flexion observed in MIN followed by MID/FF strategies (Table 3, pstrategy < 0.01).

4. Discussion

Four slip response strategies were identified for the trailing leg: MIN, FF, MID, and TD. MIN characteristics were similar to those of normal gait, while the other three had an interrupted swing phase. The TD strategy was associated with the most severe slips, followed by FF/MID and MIN responses. Interlimb coordination between the knee joint in the leading/slipping and trailing leg was found with scaling related to perturbation severity. Intralimb coordination between the hip and the knee was evident in the trailing leg. Trailing leg strategy used in a slip was found to be associated with normal gait characteristics. Finally, trailing leg responses to the slip were similar in younger and older subjects, which may be somewhat surprising. Older participants walked with a “safer” style prior to slipping [21], thus potentially compensating for other age-related deficits. Additionally, in this study, the older subjects were very healthy and not older than 67 years of age, which may explain the reported lack of aging effects.

4.1. Proposed functional role of bilateral lower extremity responses in slip-initiated recovery efforts

Net joint moments in conjunction with kinematic data provide insights into how lower extremity joints contribute to attempts to prevent slips and falls. Knee flexors in the slipping/leading leg slow the sliding motion of the foot [8]. In normal walking, an extensor knee moment in the leading leg partially contributes to the support of the trunk [22]. Thus, modulating the slipping/leading leg’s knee moment with slip severity serves two purposes; namely, reducing the perturbation magnitude while preventing body collapse. In contrast to the knee reaction, the extension response of the hip in the leading/slipping leg was not modulated by slip severity, nor associated with the response of other lower extremity joints. This finding suggests a decoupled CNS control between the hip and knee in the leading leg. One possible need for such control may be that the role of the leading/slipping leg’s hip is to provide support and to maintain the trunk upright regardless of other factors. Indeed, Kepple and colleagues demonstrated that, during the first half of the double support phase in normal walking, the hip in the leading leg contributes the most to trunk vertical support followed by the trailing leg’s ankle and by the leading leg’s knee [22].

In the trailing leg strategies involving swing phase interruption, the corrective hip extension moment is responsible for the lowering the foot onto the ground. The corrective knee flexion moment in the trailing leg can have a number of effects: (1) decelerating the swinging motion of the trailing leg; (2) absorbing the energy generated by the hip extensors; (3) allowing foot clearance of the trailing leg during swing despite the slip. Simulation studies are needed to identify the impact of the knee response in the trailing leg.

The selection of a specific trailing leg strategy interrupting swing phase may be modulated by the need for stability in a given direction. Specifically, FF responses will increase the base of support primarily in the medial–lateral direction, while MID strategy will provide greater anterior–posterior base of support than the FF response. Thus, the trailing leg

strategy plays a role in balance recovery, a critical determinate of foot placement for compensatory stepping reactions [14] and [23].

4.2. Intralimb coordination

The relatively strong correlation (r = 0.76) between the corrective moments generated by the hip (extensors) and knee (flexors) in the trailing leg is evidence of a coupling between these joints. This hip extensor–knee flexor synergy also has been found in postural responses to unexpected trips, specifically in “lowering trailing leg strategies”, which involve a premature swing phase interruption just like the MID/FF slip patterns [24]. The invariance of the intralimb coordination parameters has even been reported in gait studies imposing unusual (to the CNS) asymmetrical task constraints, e.g. gait with added weight on one limb [25], gait on a split-belt treadmill with the belt underneath each foot moving at different speeds [26], or asymmetrical fast-paced gait [27]. Findings of these studies may collectively suggest that intralimb coordination is context-independent. Yet, it is worth noting that the extent of hip–knee coupling within a limb can be modulated, as we found less coupling in the leading/slipping leg than in the trailing leg. Thus, the CNS is able to modulate the extent of coupling between the joints within a limb.

4.3. Interlimb coordination

The association between trailing leg strategy and knee response in the slipping leg implies that interlimb coordination occurs in slip-initiated postural recovery efforts. Specifically, the swing phase of the trailing leg is interrupted to prevent body collapse only when the extension moment generated by the knee in the leading/slipping leg is not sufficient (due to the foot slipping) to accept the transfer of body weight (Table 3). Thus, the association between the response of the trailing leg and that of the leading/slipping leg appears to be context-dependent. This finding agrees with other studies of interlimb coordination in humans [25], [26] and [27] and in animals [28].

4.4. Is the trailing leg response active or passive?

Finally, it may be argued that trailing leg strategies are not active responses but rather a consequence of the passive dynamics of the fall. Indeed, in stepping responses triggered during standing perturbations, Tripp and colleagues reported that the direction of the step cannot be modulated after foot lift-off [29]. This argument may hold in TD slip patterns characterized by a reduced hip extension moment in the leading leg at contralateral TO accelerating body collapse and yielding a severe slip that may not allow time for effective active trailing leg responses. The possibility that TD patterns are passively driven while other strategies are associated with active responses suggests that there may be a continuum of responses instead of discrete postural strategies. This continuum of responses would depend upon initial conditions and the modulation of active moment responses. Thus, the four trailing leg responses identified here as strategies may reflect the outcome of a more unified postural control output coupled with passive dynamics. This view would be somewhat analogous to upright standing postural responses referred to as ankle and hip strategies [30] that are blended into a mixture or continuum of these two actions depending upon the perturbation size and initial conditions [31] and [32]. Further research is required to uncover the true active and passive characteristics of recovery responses to slips.

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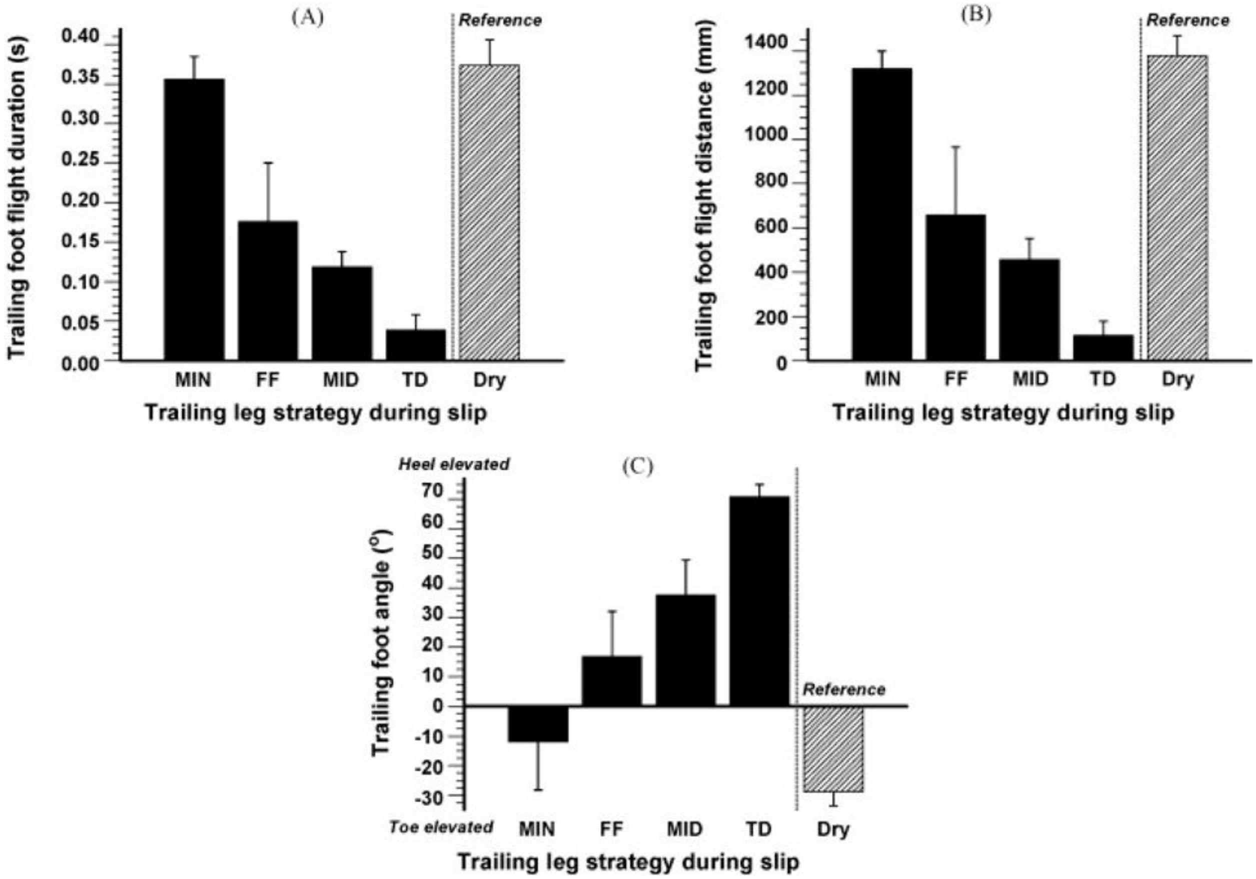

Fig. 1.

Quantitative characterization of trailing leg strategies using trailing foot flight duration (A) and distance (B) as well as foot contact angle (C). Strategy-related differences in all three variables were statistically significant ($p < 0.0001$) in both age groups. Baseline dry data averaged across all subjects are included for comparison purposes. Error bars represent standard deviations.

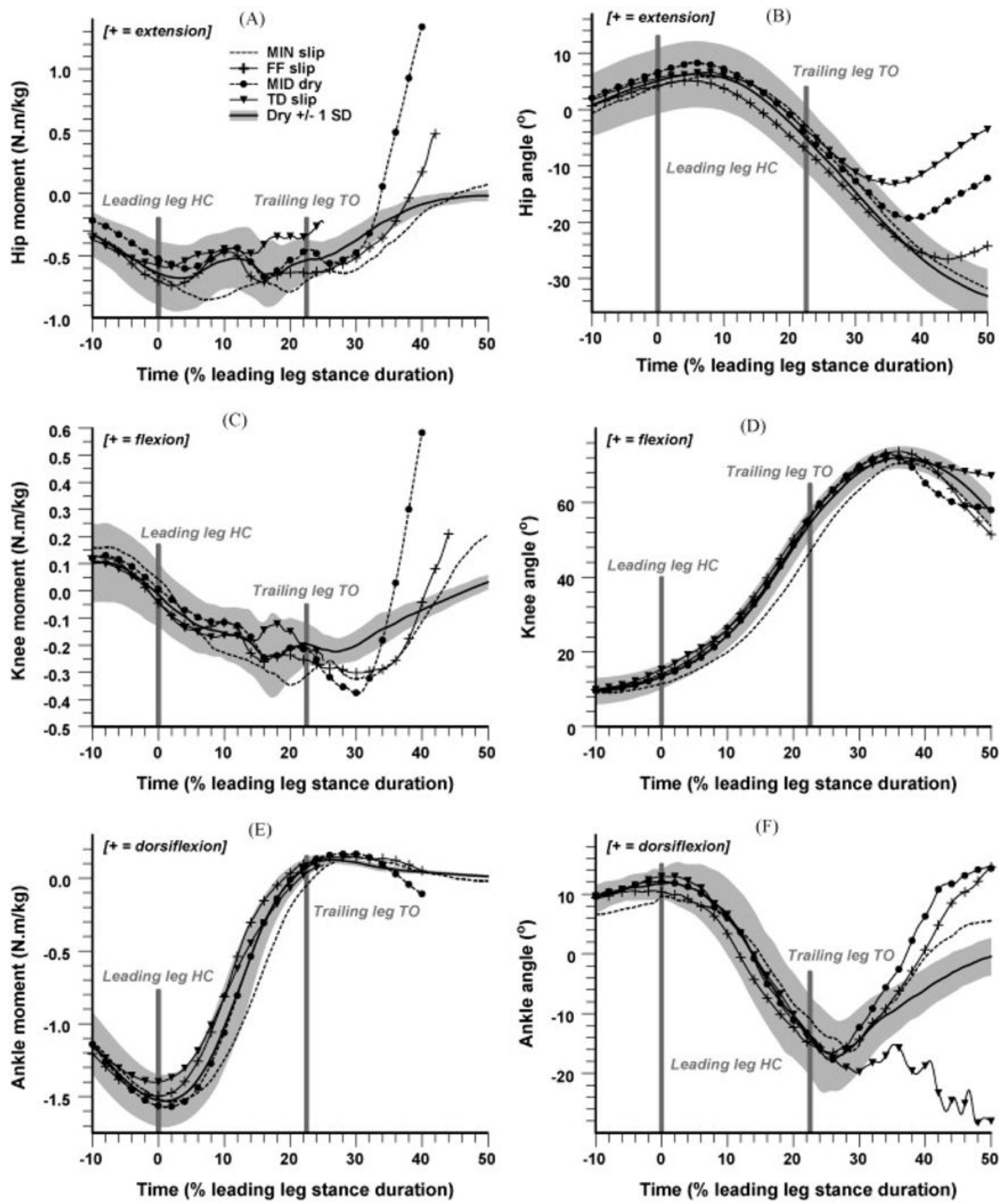

Fig. 2.

Hip, knee, and ankle sagittal joint moments (left) and angles (right) for the trailing leg. Time has been normalized to the leading leg stance duration from gait during normal walking (baseline conditions). Moment traces for slip trials are from individual representative trials and terminate prior to 50% into stance as the trailing foot often contacted the floor outside the force platform area, causing inverse dynamics calculation difficulties. Joint angles are

relative to upright standing posture and joint moments have been normalized to subject body mass.

Table 1

Mean ± S.D. onset and moment generation rate of joint moment responses stratified by trailing leg strategy (only trials with active moment response identified at the joint of interest included).

Joint								
Strategy	Leading hip response parameters		Leading knee response parameters		Trailing hip response parameters		Trailing knee response parameters	
	Onset (ms)	Rate (N m/kg s)	Onset (ms)	Rate** (N m/kg s)	Onset** (ms)	Rate* (N m/kg s)	Onset (ms)	Rate* (N m/kg s)
MIN	–	–	142 ± –	0.5 ± –^{A}	206 ± 29^{A}	12.6 ± 1.6^{A}	228 ± 31	8.8 ± 2.8^{A}
FF	189 ± 17	9.5 ± 4.0	132 ± 11	6.0 ± 1.7^{B}	213 ± 17^{A}	21.2 ± 7.6^{A}	218 ± 16	16.1 ± 6.2^{B}
MID	173 ± 26	8.7 ± 7.2	127 ± 9	5.8 ± 2.2^{B}	205 ± 14^{A}	31.8 ± 10.9^{B}	210 ± 17	19.2 ± 5.3^{B}
TD	175 ± 8	18.5 ± 5.5	118 ± 25	10.5 ± 3.2^{C}	154 ± 6^{B}	22.2 ± 12.4$^{A–B}$	189 ± 6	12.1 ± 0.8$^{A–B}$

Statistically significant difference in this parameter was found between strategies (**$p < 0.01$; *$p < 0.05$). Subsequent findings of post hoc students' *t*-tests are indicated with superscript letters, i.e. levels not connected by the same letter are significantly different ($p < 0.05$).

Table 2

Mean ± S.D. joint moments and joint angles evaluated at contralateral toe-off during normal walking, stratified by trailing leg strategy during slip.

	MIN	FF	MID	TD
Joint moments (N m/kg)				
Leading leg				
Ankle moment (+ = dorsiflexion)**	0.00 ± 0.06^{B}	0.22 ± 0.11^{A}	0.17 ± 0.10^{A}	$0.08 \pm 0.08^{A–B}$
Knee moment (+ = flexion)	−0.78 ± 0.23	−0.74 ± 0.17	−0.90 ± 0.23	−0.91 ± 0.07
Hip moment (+ = extension)**	0.55 ± 0.19^{A}	0.57 ± 0.18^{A}	0.56 ± 0.17^{A}	0.13 ± 0.06^{B}
Trailing leg				
Ankle moment (+ = dorsiflexion)	0.08 ± 0.04	0.08 ± 0.08	0.08 ± 0.04	0.08 ± 0.05
Knee moment (+ = flexion)	−0.21 ± 0.08	−0.16 ± 0.11	−0.18 ± 0.07	−0.16 ± 0.06
Hip moment (+ = extension)	−0.55 ± 0.13	−0.55 ± 0.15	−0.51 ± 0.15	−0.44 ± 0.12
Joint angles (°)				
Leading leg				
Ankle angle (+ = dorsiflexion)	−3.9 ± 2.3	−7.5 ± 3.1	−5.4 ± 2.8	−5.1 ± 3.8
Knee angle (+ = flexion)*	25.8 ± 4.8^{A}	19.6 ± 2.9^{B}	26.0 ± 4.8^{A}	$23.9 \pm 2.5^{A–B}$
Hip angle (+ = extension)	−30.4 ± 2.6	−29.3 ± 5.0	−31.4 ± 6.2	−29.3 ± 4.5
Trailing leg				
Ankle angle (+ = dorsiflexion)	−13.6 ± 4.6	−11.7 ± 7.8	−15.4 ± 6.1	−14.2 ± 7.3
Knee angle (+ = flexion)	53.4 ± 4.2	53.1 ± 5.4	55.6 ± 4.1	56.5 ± 4.5
Hip angle (+ = extension)	−5.4 ± 4.3	−5.2 ± 7.5	−4.4 ± 6.0	−4.9 ± 1.0

Statistically significant difference in this parameter was found between strategies (** $p < 0.01$; * $p < 0.05$). Subsequent findings of post hoc students' *t*-tests are indicated with superscript letters, i.e. levels not connected by the same letter are significantly different ($p < 0.05$).

Table 3

Mean ± S.D. joint moments and joint angles evaluated at toe-off of the trailing leg during the slip, stratified by trailing leg strategy subsequently used in the same trial.

	MIN	FF	MID	TD
Joint moments (N m/kg)				
Leading leg				
Ankle moment (+ = dorsiflexion)**	0.01 ± 0.07^{B}	0.30 ± 0.08^{A}	0.27 ± 0.09^{A}	0.12 ± 0.04^{B}
Knee moment (+ = flexion)**	−0.48 ± 0.13^{C}	−0.30 ± 0.12^{B}	−0.24 ± 0.12^{B}	0.15 ± 0.02^{A}
Hip moment (+ = extension)	0.70 ± 0.32	0.64 ± 0.19	0.60 ± 0.21	0.37 ± 0.09
Trailing leg				
Ankle moment (+ = dorsiflexion)	0.09 ± 0.03	0.10 ± 0.09	0.07 ± 0.04	0.05 ± 0.03
Knee moment (+ = flexion)	−0.25 ± 0.07	−0.22 ± 0.16	−0.20 ± 0.09	−0.19 ± 0.04
Hip moment (+ = extension)*	−0.65 ± 0.15^{B}	−0.60 ± 0.20^{B}	−0.46 ± 0.24^{A}	−0.33 ± 0.16^{A}
Joint angles (°)				
Leading leg				
Ankle angle (+ = dorsiflexion)	−7.5 ± 1.7)	−10.6 ± 3.6)	−10.5 ± 4.1)	−10.9 ± 6.8)
Knee angle (+ = flexion)**	22.2 ± 5.2)^{A}	12.9 ± 3.7)^{B}	14.6 ± 3.4)^{B}	3.2 ± 0.5)^{C}
Hip angle (+ = extension)	−29.2 ± 3.3)	−29.4 ± 4.9)	−30.9 ± 6.8)	−27.0 ± 5.0)
Trailing leg				
Ankle angle (+ = dorsiflexion)	−13.7 ± 4.5	−12.3 ± 8.0	−13.7 ± 6.5	−15.1 ± 3.2
Knee angle (+ = flexion)	53.2 ± 4.4	53.2 ± 6.3	56.2 ± 6.9	58.0 ± 5.1
Hip angle (+ = extension)	−6.2 ± 4.9	−5.2 ± 7.5	−4.7 ± 7.9	−4.3 ± 1.8

Statistically significant difference in this parameter was found between strategies (**$p < 0.01$; *$p < 0.05$). Subsequent findings of post hoc students' *t*-tests are indicated with superscript letters, i.e. levels not connected by the same letter are significantly different ($p < 0.05$).