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PREDICTED THRESHOLD AGAINST BACKWARD BALANCE LOSS FOLLOWING A SLIP IN GAIT

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Abstract

The purpose of this study was to use a 7-link, moment-actuated human model to predict, at liftoff of the trailing foot in gait, the threshold of the center of mass (COM) velocity relative to the base of support (BOS) required to prevent backward balance loss during single stance recovery from a slip. Five dynamic optimization problems were solved to find the minimum COM velocities that would allow the simulation to terminate with the COM above the BOS when the COM started 0.25, 0.5, 0.75, 1.0, and 1.25 foot lengths behind the heel of the stance foot (i.e., behind the BOS). The initial joint angles of the model were based on averaged data from experimental trials. Foot-ground contact was modeled using 16 visco-elastic springs distributed under the stance foot. Slipping was modeled by setting the sliding coefficient of friction of these springs to 0.02. The forward velocity of the COM necessary to avoid a backward balance loss is nearly two times larger under slip conditions than under non-slip conditions. The predicted threshold for backward balance loss following a slip agreed well with experimental data collected from 99 young adults in response to 927 slips during walking. In all trials in which a subject's COM had a velocity below the predicted threshold, the subject's recovery foot landed posterior to the slipping foot as predicted. Finally, combining experimental data with optimization, we verified that the 7-link model could more accurately predict gait stability than a 2-link model.

Keywords

computational biomechanics; dynamic stability; optimization; adaptation; fall prevention

INTRODUCTION

Falls initiated by slipping account for about 25% of all falls among older people (Holbrook, 1984). Backward falls from a slip frequently cause hip fracture that can have devastating consequences (Kannus et al., 1999). A better understanding of the mechanisms underlying backward loss of balance (BLOB) a precursor to slip-related falls will undoubtedly be an important step towards the prevention of such injuries.

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A primary objective for the central nervous system during slip recovery is to control the relative motion state (the position and velocity) between the body center of mass (COM) and its base of support (BOS). At liftoff when a person's COM is posterior to the BOS of the stance limb, the forward velocity of the COM must exceed a certain threshold to be carried to a point over the slipping BOS. Below this threshold, the velocity will diverge from its desired forward trajectory, diminish under the influence of gravity, eventually reverse its direction, potentially leading to a backward fall.

Although the stability boundary against BLOB in gait has been determined for non-slip conditions (Yang et al., 2007), the extent to which it is altered by slip conditions is unknown. A 2-link human model simulation for bilaterally symmetrical standing has shown that this boundary for slipping conditions is very different from that for non-slip conditions (Pai and Iqbal, 1999). It is possible, as recently revealed (Yang et al., 2007), that a 7-link human model may potentially provide more realistic results than did the 2-link model in simulating a slip in gait.

Previous studies have postulated that the lower limb joint moments play important roles in adjusting the body configurations and consequently regaining balance in response to a forward slipping perturbation (Cham and Redfern, 2001; Ferber et al., 2002; Tang et al., 1998). Such reactive response could be improved with motor training, resulting from improvement of one's dynamic stability (Bhatt et al., 2006a; Bhatt et al., 2006b; Pavol and Pai, 2002) and adaptation to "skate-over" and "walkover" strategies (Bhatt et al., 2005). The stability boundary derived from a joint-moment-actuated model can thus provide a quantitative basis to assess one's stability limitations (Pai et al., 2003), and could be a valuable tool to quantify such adaptive training (Bhatt et al., 2005; Bhatt et al., 2006b).

The purpose of this study was to use a 7-link, moment-actuated human model to predict, at liftoff of the trailing foot in gait, the threshold of the relative COM velocity ($\dot{x}_{COM}^{initial}$) required to prevent BLOB during single stance recovery from a slip. This new boundary was then contrasted with the findings from the 2-link model for slip conditions (Pai and Iqbal, 1999) and the 7-link gait model for non-slip conditions (Yang et al., 2007). Experimental data on slips induced during walking were also applied to verify the model predictions.

METHODS

A previously developed bipedal model (Yang et al., 2007) in OpenSim (Delp et al., 2007), with right foot as the slipping foot, was used to simulate the motion of the COM (Fig. 1). Nine generalized coordinates, $\mathbf{q} = [x, y, \theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6, \theta_7]$, were applied to define the body motion. The same actuator mechanism and foot contact model were used as our previous study (Yang et al., 2007). The details to calculate the joint moment, τ , from the joint excitation, u , can be found in the online supplement. Equations of motion for the model were derived using SD/Fast (PTC, Needham, MA). All state equations for the model were integrated using a Runge-Kutta-Feldberg 5–6 variable-step integrator (Atkinson et al., 1989).

The threshold against BLOB was computed with the model starting at a specific position. The initial horizontal position of the COM relative to the BOS, $x_{COM}^{initial}$, was systematically varied from starting even with the right heel (i.e., $x_{COM}^{initial} = 0$) to 1.25 foot lengths posterior to the right heel (i.e., $x_{COM}^{initial} = -1.25$) in increment of -0.25 . The initial conditions including the right heel velocity, and the joint angles $\theta = [\theta_1 \theta_2 \dots \theta_7]$, were derived from the body configurations at left liftoff during gait experiments (see below). Simulation times, ranging from 0.28 to 0.44 s, were set based on the duration from left liftoff to its touchdown averaged across all the

experimental trials at the corresponding $x_{COM}^{initial}$. The slipping condition was simulated by setting the coefficient of friction between the sole and the ground to 0.02; no constraints were placed on the slip.

At each $x_{COM}^{initial}$, simulated annealing (Corona et al., 1987) was used to find the optimal $\theta^{initial}$ and $u_i(t)$, $i=1,2,\dots,6$, that would minimize the cost function,

$$\begin{aligned}
 f = & w_1 \cdot x_{COM}^{initial} \\
 & + w_2 \cdot \int_{t_i}^{t_f} [F_y(t)] dt + w_3 \cdot \int_{t_i}^{t_f} e(\theta(t)) dt + w_4 \cdot \int_{t_i}^{t_f} e(\dot{\theta}(t)) dt + w_5 \cdot \sum_{i=1}^6 \int_{t_i}^{t_f} (u_i(t))^2 dt \\
 & + w_6 \cdot \int_{t_i}^{t_f} [\dot{x}_{BOS,peak} - \dot{x}_{BOS}(t)] dt + w_7 \cdot \int_{t_i}^{t_f} [\ddot{x}_{BOS,peak} - \ddot{x}_{BOS}(t)] dt \\
 & + w_8 \cdot \int_{t_i}^{t_f} [\min(y_{1,toe}(t), y_{1,heel}(t))] dt \\
 & + w_9 \cdot |x_{COM}^{final}| + w_{10} \cdot |x_{heel}^{final}| + w_{11} \cdot |x_{COM}^{final}| + w_{12} \cdot |\dot{x}_{COM}^{final}|
 \end{aligned} \quad (1)$$

where w_i is the weight of the i^{th} term, the subscript *peak* indicates the peak value of the corresponding items measured in experiments. The subscripts l_{heel} and l_{toe} respectively indicate left heel and toe. The t_i (left liftoff) and t_f are the initial and final time of the simulation, respectively. Symbols $x/\dot{x}/\ddot{x}_{COM}$ represent the position/velocity/acceleration of the COM relative to the right heel, respectively. The symbol $\lfloor s \rfloor$ has the following behavior:

$$\lfloor s \rfloor = \begin{cases} 0 & s > 0 \\ -s & s \leq 0 \end{cases}$$

$e(s)$ is computed using the equation,

$$e(s(t)) = \sum_{i=1}^7 \varphi(s_i(t)), \text{ where } \varphi(s_i) = \begin{cases} s_i^- - s_i & s_i < s_i^- \\ 0, & s_i^- \leq s_i \leq s_i^+ \\ s_i - s_i^+ & s_i > s_i^+ \end{cases}$$

s_i^- and s_i^+ represent the lower and upper bounds, respectively, of the feasible range of the variable s_i . Here they indicate the physical limits of the angle and angular velocity of the i^{th} joint.

The first term in Eq. (1) ensured that $x_{COM}^{initial}$ would be the minimum necessary to avoid BLOB. The second term required that the resultant vertical ground reaction force under right foot, F_y , remain positive. The third and fourth terms restricted θ and $\dot{\theta}$ to remain within the physical limits determined by experimental data (Luttgens and Hamilton, 1997). To facilitate convergence in this first attempt to simulate gait and slip recovery, we adopted a common scheme (Nubar and Contini, 1961; Redfield and Hull, 1986) to minimize the integral of the square of the torque (term 5). The sixth and seventh terms constrained the horizontal velocity and acceleration of the right heel to remain below the corresponding peak values observed in gait experiments. The eighth term prevented the left foot from contacting the ground during the movement. The ninth and tenth terms required the COM to lie inside the BOS at the end of the simulation, and the left heel to remain forward of the right heel at the point when the relative motion between the COM and BOS diminished at termination of the simulation – a condition guaranteed by the last two terms.

The results derived from the optimization problem were qualitatively evaluated in two ways. First, the computed threshold was compared with experimental data to verify whether the

threshold could successfully predict the outcomes of slip recovery. Second, if discrepancies between the simulations by 2- and 7-link models emerged, we then chose a COM state lying in the region of difference between the two predictions and determined whether the outcome of BLOB determined by one model could in fact be further optimized by the other model. In a similar simulation process, the *experimentally* derived motion state of each segment at liftoff was used to generate $\dot{x}_{COM}^{initial}$. The first term in Eq. (1) was, therefore, eliminated during an otherwise identical optimization process. The simulation result was then compared with the experimentally derived data to inspect the amount of improvement in performance (Yang et al., 2008) due to the optimization of joint kinetics.

Three separate sets of experimental gait data derived from 927 trials among 99 young adults (Bhatt and Pai, 2007; Bhatt et al., 2005; Bhatt et al., 2006b) were pooled for this verification (Table 1). Slips were induced with a device consisting of a passively moveable platform mounted on a low-friction linear bearing on a supporting frame (Yang and Pai, 2007). Full body gait kinematics and kinetics were respectively low-pass filtered at 4.5–9 (marker specific) and 27 Hz using fourth-order Butterworth filters. The outcome of each trial was identified based on the relative position of the feet at recovery touchdown: a BLOB was operationally defined as to occur when the trailing foot landed posterior to the slipping foot.

RESULTS

The predicted threshold values against BLOB during slipping induced in gait for all 5 $\dot{x}_{COM}^{initial}$ are shown in Table 2. A more posterior $x_{COM}^{initial}$ required a greater $\dot{x}_{COM}^{initial}$ to bring the COM over the BOS. The velocity threshold ranged from 0, when $x_{COM}^{initial}=0$, to 0.521, when $x_{COM}^{initial}=-1.25$. Inspection of the results from a simulation ($x_{COM}^{initial}=-0.75$, Fig. 2) revealed that the optimization routine yielded a solution that satisfied the cost function. θ , $\dot{\theta}$, and τ remained within physiological ranges, and the left foot was above ground throughout the simulation. At movement termination, the left heel was anterior to the right heel and the COM was just within the BOS and at rest relative to the BOS.

Within the simulated range of COM positions, the threshold values against BLOB under slip conditions were higher than those under non-slip conditions derived from the same 7-link model for walking (Table 2, Fig. 3, solid vs. dotted line). The threshold values during slipping derived by the 2-link and the 7-link models were very similar in three of the five simulation cases (Table 2, Fig. 3, solid vs. dashed line). In the other two cases ($x_{COM}^{initial}=-0.50$ and -0.25), the threshold velocities from the 7-link model were 4% and 22% greater than those from the 2-link model, respectively (Table 2).

In all subjects whose COM had a velocity below the predicted threshold, their recovery foot landed posterior to the slipping foot precisely as predicted (Fig. 4, Table 3). Subjects' foot landed posterior to the slipping foot in 31 of 249 trials (12%), when their velocity was in fact above the predicted threshold. The results of the 7-link model were better than those of the 2-link model (Pai and Iqbal, 1999), where this disagreement occurred in 46 (18%) trials.

This finding was further supported when the model simulation began at a COM state below the threshold from the 7-link model but above threshold from the 2-link model (Pai and Iqbal, 1999). The optimizer was unable to find a solution that satisfied the terminal conditions for stability (Fig. 5). The optimization method employed in the present study could improve the dynamic stability of the person, but such improvement was still insufficient to reach above the threshold level as predicted by the 7-link model (Fig. 5, dashed vs. dash-dotted line). The kinetic profile was similar between simulated and experimental results (Fig. 6).

DISCUSSION

Overall, our results indicate that the threshold against BLOB under slip conditions derived from a 7-link model were remarkably similar to those derived from a 2-link model. Nonetheless, the accuracy of the results derived from the 2-link model could still be improved by using the 7-link model, and such improvements were indeed verified with empirical data (Table 2 and Fig. 4) combined with analytical means (Fig. 5). The discovery of such improvements at $x_{COM}^{initial} = -0.25$ and -0.50 is important because this is a functional range (Bhatt et al., 2006b) where most volitional gait patterns and spontaneous recovery responses following a slip occur (Bhatt et al., 2005) (Fig. 4).

The boundary for slip conditions derived by the same 7-link model lies above that for non-slip conditions (Fig. 2); that is, $\dot{x}_{COM}^{initial}$ at a given $x_{COM}^{initial}$ for slip conditions is greater than that for non-slip conditions. This general finding (Pai and Iqbal, 1999) has provided insights into the adaptive behavior of the motor control system when subjects were exposed to repeated slips (Bhatt et al., 2006b; Pavol and Pai, 2002). Consistent with the model predictions, successful adaptation to repeated slips is characterized by an anterior shift of the COM and/or an increase of the COM velocity, both prior to and following the slip onset, whether it is induced during sit-to-stand (Pavol and Pai, 2002) or in gait (Fig. 4) (Bhatt et al., 2006b). The stability boundary has enabled researchers, for the first time, to quantify and distinguish adaptive improvements and motor memory retention (Bhatt and Pai, 2005; Bhatt et al., 2006a).

The current boundary is quantitatively derived, and is based on Newton's second law, Borelli's classic definition of standing balance (Borelli, 1680), well-known physiological and environmental constraints, and optimal solutions. On the other hand, the decision to place the swing leg posterior to the slipping foot will depend upon, not only the physical stability limits, but also human perception and the complicated interaction between the cognitive and the sensorimotor system (Pai et al., 2003). The model prediction disagrees with experimental outcome in 31 out of 249 experimental trials (12%). Significant sensory and/or motor deficits, frailty, anxiety, or personal preference can contribute to and accentuate this mismatch. It is possible that a person takes an "unnecessary" step because of a lack of physical strength or quickness, although such a scenario seems to be less likely among more active and healthy individuals (McIlroy and Maki, 1996; Mille et al., 2003; Pai et al., 2006; Pavol et al., 1999; Thelen et al., 1997). In reality, taking a recovery step, even if it is unnecessary, is a very desirable and prudent protective strategy commonly adopted by older adults (Maki and McIlroy, 1997; Pai, 2003).

In almost all of these 31 trials, subjects' COM states were located in the *same* feasible stability region as other trials in which the *same* subjects did successfully step forward, indicating that such outcomes were optional. Although in our experimental paradigm we had explicitly instructed the subjects to walk forward following a slip, we could not verify that the observed posterior step landing was necessary. A previous study found that as much as 41% of backward steps following a forward perturbation in standing might have been unnecessary (Pai et al., 2000). None of these 31 "unnecessary" steps occurred during the first slip in which the likelihood of an "optional" foot landing location is near zero due to the severe destabilization (Bhatt et al., 2005). When a subject's COM state at liftoff is located outside the feasible stability region, this person has *no option* but to take a recovery step to prevent the body from falling. This may explain why we have a 100% success rate in predictions outside of the feasible stability region (Table 3).

Unlike the operational definition applied in experimental verification, the definition for balance loss in model simulation does not solely rely on where model's left foot landed. Rather, its

terminal condition represents an extreme case (i.e., gait termination) for a successful recovery that is based on Borelli's definition of the stability limits (Borelli, 1680), which is also a broadly accepted operational definition in contemporary physical rehabilitation practice (O'Sullivan, 1994). This extreme case was different from what happened in our experiments, in which the subjects successfully followed instruction and continued walking following a slip. Such differences could account for the model and experimental differences observed in the COM state trajectories (the dash-dotted line in Fig 3 and dotted lines in Fig. 4). On the other hand, Figs 5 and 6 clearly show that kinematics and kinetics were at least in the "same ballpark" when the experimental and simulated conditions were similar. Therefore, we expect that the COM state trajectory in Figs 3 and 4 could have been better matched if subjects were explicitly instructed to maintain upright standing following the slips rather than to keep walking. Independent of how one might define BLOB, it is of theoretical and clinical interest to determine the threshold velocity which is insufficient to bring the COM over the BOS, thus requiring one to take measures, such as lowering the swing leg to the ground, to arrest the backward fall.

It is important to note several limitations in our approach. To simplify our human model, motion of the upper limbs was excluded. Little evidence has shown that the upper limbs may be helpful in recovering from balance loss (Marigold et al., 2003; Tang et al., 1998). When the upper limbs are not in contact with surrounding support surface, their effect on the stability limits could be limited and remains an open question for future investigation. The model used here also only considered motion in the sagittal plane. Motion along the mediolateral direction and rotation of the pelvis around the vertical axis may result in changes of the COM motion state, which might cause some variance in the threshold values against BLOB.

Finally, the moveable-plate setup used to induce slips in experiments does not precisely reproduce the "free" slips induced by lubricant material (Troy and Grabiner, 2006), which could also affect the model verification. The plate used here adds inertia and constraint to the foot (Yang and Pai, 2007) that does not exist in "free" slipping; this, then, could possibly reduce the peak velocity of the slip and limit mediolateral foot displacement. Nevertheless, the kinematic response profiles obtained in the moveable-plate setup (Bhatt et al., 2005) was at least comparable to that recorded in "free" slips induced by lubricant material (Lockhart et al., 2003; Redfern et al., 2001; You et al., 2001).

Despite these limitations, the credibility of the results is supported by two independent sources. First, extensive experimental data from a very large sample size were highly supportive of the model simulation results (Fig. 4). Second, combining experimental data with optimization, we used a similar simulation approach to evaluate the discrepancies, and verified that the 7-link model was indeed more accurate than the 2-link one in predicting dynamic stability during walking (Fig. 5). The close resemblance in the simulation and experiment results (Figs. 5 and 6) also provides some idea of how well our simulation worked in a "failed recovery". Using sensitivity analysis, simulation and optimization with this model can enable us to investigate the causal effect of strength and BOS limitations (Pai and Patton, 1997) that would be difficult to elucidate with experimental methods due to its inability to control or eliminate the effect of the confounding factors. These aspects highlight the differences between the analytical and empirical approaches – each yields unique, irreplaceable perspectives, yet complimentary when they are combined.

In summary, the present study determined the feasible stability boundary against BLOB following a slip during walking. The threshold provides a quantitative basis for assessing one's dynamic stability during gait, and predicted changes between the slip and non-slip conditions provide guidelines for adaptive training and understanding of human motor memory decay.

Establishing a retainable training regimen against slip-related falls would, without doubt, have major public health benefits (Bhatt and Pai, 2005; Bhatt et al., 2006a).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Schematic of the 7-link, 9-degree-of-freedom, sagittal-plane model of the human body. The vector $\mathbf{q} = [x, y, \theta_1, \theta_2, \dots, \theta_7]$ represents the generalized coordinates of the model. Generalized coordinates x , y , and θ_1 specify the position and orientation of the right foot, which is the slipping foot and the base segment of the model following the left foot liftoff after slipping perturbation, with reference to the inertial reference frame (X, Y, Z) . Joint angles θ_i ($i=2,3, \dots, 7$) correspondingly specify the angles of the ankle, knee, hip of the right limb (solid line) and the hip, knee, and ankle of the left limb (dashed line). The location of the center of mass for each segment, shown as the half-shaded circle, as well as the proportion of segment length, mass, and moment of inertia for a person of 1.82 m and 73.1 kg, has been provided previously (Anderson and Pandy, 1999). The positive X -axis is in the direction of forward progression, and the positive Y -axis is upward. Positive joint rotation is along the positive Z -axis (counterclockwise) for the right limb (solid line), and its sign is reversed (clockwise) for the left limb (dashed line).

Fig. 2.

A representative simulation result of the joint angular displacement (a–c), joint angular velocity (d–f), vertical ground reaction force under the right foot (g), horizontal velocity of the right heel and relative velocity of the center of mass (COM) to the right heel (BOS) (h), horizontal acceleration of the right heel and relative acceleration of COM to the BOS (i) time history, and the corresponding stick-figure animation sequence (j) of a successful balance recovery following a slip in walking with an initial center of mass (COM) position of -0.75 (normalized to foot length). The solid and dashed lines respectively represent the right and left sides in (a–f) and (m); they represent the horizontal velocity/acceleration of right heel and relative velocity/acceleration of COM to the BOS in (h–i). Positive values indicate ankle plantar-flexion, knee flexion, and hip extension. The five-pointed star marks the COM position of the stick-figure and the shaded triangle is the starting position of the right heel at left foot liftoff. The corresponding COM motion state trajectory for this simulation trial is shown in Fig. 3. The numbers shown in the middle bracket in (a–f) indicate the physical range used in the *cost function*. The numbers in the middle bracket in (h–i) represent the peak values derived from the gait experiments and used in the *cost function*. The ground reaction force is normalized to body weight (bw).

Fig. 3.

The feasible stability boundary against backward balance loss, derived from interpolation of six threshold values of initial center of mass (COM) velocity, required at corresponding normalized initial COM positions to prevent backward balance loss. COM velocity is relative to the base of support (BOS), $\dot{x}_{COM}$. COM positions x_{COM} decrease from -1.25 to 0 , with a constant interval of -0.25 . Comparisons are made between the boundaries corresponding to the 7-link model of the present study for walking, slip conditions (solid line) and non-slip conditions (dotted line, Yang et al., 2007), and for the 2-link model for standing (dashed line, Pai and Iqbal, 1999). The dash-dotted line with an open diamond represents an individual result of the simulated COM state trajectory for a given initial COM position of -0.75 in the present study. x_{COM} and $\dot{x}_{COM}$ are dimensionless variables expressed as a fraction of l_{BOS} and $\sqrt{g \times bh}$, respectively, where l_{BOS} represents the length of the foot, g is the gravity constant, and bh is the body height. For the COM position, negative values indicate that the COM is posterior to the right heel; zero value implies that the COM is at the posterior edge of the right heel.

Fig. 4.

The experimentally derived initial center of mass (COM) state values at left foot liftoff following a slip in gait. Panel (a) shows those trials which resulted in a backward loss of balance (BLOB, $n = 249$), panel (b), those which resulted in no loss of balance (NLOB, $n = 678$). The dotted lines in (a) and (b) represent the COM motion state trajectory of two typical experimental trials from left liftoff to touchdown; these resulted in BLOB and NLOB, respectively. Also shown are the stability boundaries against BLOB derived in the present study (solid line) and a previous study (dashed line, Pai and Iqbal, 1999). The subjects' stability deteriorated further during single stance phase in trials with recovery foot landed posterior to the slipping foot in (a). In contrast, the subjects' stability against BLOB progressively improved during the same phase in trials with recovery foot landed anterior to the slipping foot in (b). The COM position was computed from kinematic data using known gender-dependent segmental parameters in a 13-segment representation of the body (de Leva, 1996). The COM velocity was calculated by differentiating the COM position data with respect to the time. The COM position and forward velocity relative to the base of support (BOS) are dimensionless variables expressed as a fraction of l_{BOS} and $\sqrt{g \times bh}$, respectively, where l_{BOS} represents the length of the foot, g is the gravity constant, and bh the body height.

Fig. 5.

Experimentally derived center of mass (COM) motion state trajectory (dash-dotted line) for an unsuccessful balance recovery trial and the corresponding simulation result (dotted line). This experimental trial was chosen because the subject experienced a backward balance loss (same subject and trial as Fig. 4-a, dotted line) and because its initial state was inside the feasible stability region of the 2-link model but outside that of 7-link model. The circle and diamond mark the initial COM state at liftoff for the model and the subject, respectively. Also shown are the stability boundaries against backward balance loss derived from the 7-link (solid line) and the 2-link model (Pai and Iqbal, 1999, dashed line). Clearly, the optimized trajectory from the simulation was more stable (with a higher velocity value at a given COM position) than the actual performance throughout the majority of single stance. However, such improvement was insufficient to reverse the termination condition to allow a recovery; the COM was still significantly behind the right heel when its horizontal velocity reduced to zero.

Fig. 6.

Experimentally-derived joint moments at the lower limb on the slipping side (dashed line) for a loss of balance trial and the corresponding simulation results (solid line) for a 71.2kg and 1.65m subject. The corresponding center of mass (COM) motion state trajectory is shown in Fig. 5. Also shown are the strength limitations for each joint (thin horizontal lines and the numbers close them) used in the *cost function*. The joint moments are normalized to the body mass. Positive values indicate ankle plantar-flexion, knee flexion, and hip extension. The profiles of the kinetics of the simulation results and the experimentally-derived kinetic data are in the same “ballpark”.

Table 1

The number of subjects and slipping trials in each set of experimental gait analysis data pooled for the purpose of verification of model predictions.

Number of subjects	Number of trials		Total
	First session	Re-test sessions	
32 [*]	121 (5)	0	121
24 ⁺	553 (24)	211 (2–4)	764
43 [§]	42 (1)	0	42
Total	716	211	927

The number in parentheses indicates the number of the slipping trials per person in the respective session(s).

^{*} data from Bhatt, et al., 2005;

⁺ data from Bhatt, et al., 2006a;

[§] data from Bhatt, et al., 2007.

Table 2

The initial center of mass (COM) horizontal velocities relative to the BOS ($\dot{x}_{COM}^{initial}$), necessary to prevent backward balance loss for slipping, derived by the 7-link model and a 2-link model, as well as the necessary initial COM velocity under non-slip condition, derived by the 7-link model at all simulated initial COM positions ($x_{COM}^{initial}$).

	Conditions	Position ($x_{COM}^{initial}$)				
		-1.25	-1.00	-0.75	-0.50	-0.25
Velocity ($\dot{x}_{COM}^{initial}$)	Slip	0.521	0.460	0.386	0.292	0.175
	2-link model*	0.517	0.462	0.383	0.281	0.143
	7 link model ⁺	0.290	0.259	0.213	0.150	0.075

The $\dot{x}_{COM}^{initial}$ and $x_{COM}^{initial}$ are dimensionless variables expressed as a fraction of l_{BOS} and $\sqrt{g \times bh}$, respectively, where l_{BOS} represents the length of the foot, g is the gravity constant, and bh is the body height. For the COM position, negative values indicate that the COM is posterior to the right heel; zero value implies that the COM is at the posterior edge of the right heel.

* data from Pai and Iqbal, 1999;
⁺ data from Yang et al., 2007.

Table 3

Number of experimental trials in which the experimental outcomes either agreed (regular) or disagreed (bolded) with predicted results. Agreement or disagreement with a previous 2-link model (Pai and Iqbal, 1999) is shown in parentheses. Predicted and experimental outcomes are indicated as a backward loss of balance (BLOB) or no loss of balance (NLOB).

		Model Prediction	
		BLOB	NLOB
Experiment	BLOB N=249	218 (203)	31 (46)
	NLOB N=678	0 (0)	678 (678)