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Possible recovery or unavoidable fall? A model to predict the one step balance recovery threshold and its stepping characteristics

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ABSTRACT

In order to prevent fall related injuries and their consequences, one needs to be able to predict the outcome of a given balance perturbation: a possible Balance Recovery (BR) or an unavoidable fall? Given that results from the existing experimental studies are difficult to compare and to generalize, we propose to address this question with a numerical tool. Built on existing concepts from the biomechanics and robotics literature, it includes the optimal use of BR reactions and particularly the possibility to perform a recovery step. It allows estimating 1) the possibility to recover a steady balance from a given initial state or perturbation using at most one recovery step; 2) the set of recovery steps leading to a BR. Using standard sets of parameters for young and elderly population, we assessed this model's predictions against experimental data from the literature in the anterior direction. Two classical representations of the human body (inverted pendulum (IP) vs. linear inverted pendulum (LIP)) were also compared. The results showed that the model correctly predicted the possibility to recover using a single protective step (1-Step BR threshold) and the characteristics (step length and time) of the protective step for both the young and the elderly. This tool has a real potential in the field of fall prevention to detect risky situation. It could also be used to get insights into the neuromuscular mechanisms involved in the BR process.

1. Introduction

A fall is a common event that everyone can encounter throughout their life. Consequences can be extremely severe such as hip fracture, upper limb injuries or traumatic brain injuries especially for frail people such as the elderly. The average cost of one fall injury is about 1049$ in the US with 28–35% of people over 65 years falling each year (World Health Organization, 2008). These figures highlight the necessity for better fall prevention.

In this context, BR thresholds are an important variable to predict the perturbations that may lead to a fall. They can also be used to identify different BR performances between population groups or to better understand the neuromuscular mechanisms involved in the BR process. Note that in this study we define a BR by the action to restore a steady standing state, i.e. the Center of Mass (CoM) above the Base of Support (BoS) with a null velocity.

BR thresholds have been experimentally assessed for different population groups, using various kinds of perturbations (tether-release, pull force, slip) and different instructions about the way to recover (Bariatinsky, 2013; Carbonneau and Smeesters, 2014; Cyr and Smeesters, 2009; Do et al., 1999; Hsiao-Wecksler and Robinovitch, 2007; King et al., 2005; Madigan and Lloyd, 2005; Mille et al., 2003; Wojcik et al., 1999). In particular Cyr and Smeesters (2007) showed that the BR threshold obtained when only one recovery step is allowed (1-Step BR threshold) is a good approximation of the maximal state or external perturbation that can be handled without falling.

Although interesting, these experimental data are very specific (i.e. perturbation, population and instruction dependent) and cannot be easily compared between studies. They are also hardly generalizable and their use to predict the outcome of a non-tested condition is limited. Moreover, they did not allow a complete identification of the role and influence of the different physiological parameters involved in the BR process. Consequently, a numerical model that can estimate the 1-Step BR thresholds for various populations, perturbations and instructions, is a necessary complement to these experimental observations.

One of the main difficulties in obtaining such a model is the necessity to include the automatic postural responses and the

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voluntary reactions to the balance disturbances. Some studies explicitly include a regulation of BR actions based on the system state and/or perceived perturbation (Atkeson and Stephens, 2007; Peterka, 2002; Van der Kooij et al., 1999, Aftab et al., 2012). However, the control of BR reactions tends to limit these models usability (close-loop controller requirement, additional parameter adjustments, etc.). A pragmatic alternative to estimating only the BR thresholds is to consider only the most efficient BR reactions. Based on this idea the possibility to avoid a fall using a fixed support strategy, i.e. without performing a recovery step, was first assessed by Pai and Patton (1997). They represented the human body by an Inverted Pendulum (IP) and the recovery actions by the development of a maximal eccentric ankle joint torque. This approach was further simplified by Hof et al. (2005) and Pratt et al. (2006) who used a Linear Inverted Pendulum (LIP), i.e. a pendulum that travels at a constant height (Kajita and Tani, 1991), and replaced the eccentric ankle joint torque by the displacement of the Center of Pressure (CoP) within the Base of Support (BoS). The possibility to avoid a fall can be estimated from the current state of the Center of Mass (CoM) and expressed as the inclusion of a specific point, named eXtrapolated Center of Mass (XCoM) or Capture Point (CP) (the first denomination will be used in this study), within the BoS. Hof et al. (2005) showed the validity of the pendulum linearization by comparing their results to those of Pai and Patton (1997). Pratt et al. (2006) also included an additional BR mechanism (the angular momentum control due to the rotation of body segments) by adding a flywheel (FW) centered at the CoM. Eventually further works included recovery steps. Wu et al. (2007) complemented the model from Pai and Patton (1997) to include a single step which duration is driven by the system's geometry and Koolen et al. (2012) extended the works from Pratt et al. (2006) to include multiple steps with a constant length and duration.

These later developments are conceptually very interesting and already used in robotics. However they still suffer from limitations. Firstly they lack validation against human data. Moreover there is no step length/duration regulation although it is known to play a critical role in the BR process (Hsiao-Wecksler and Robinovitch, 2007; Owings et al., 2001; Thelen et al., 1997). Lastly the CoM evolution before the recovery step landing – IP (Wu et al., 2007) vs. LIP (Koolen et al., 2012) – still needs to be clarified (Aftab et al., 2010; Li et al., 2014).

Consequently, the objective of this study is to propose a simple numerical tool that predicts if a balance perturbation (external perturbation or initial unbalanced state) can be recovered using a single recovery step. It is based on the previous developments and aims to overcome their current limitations: it includes step length/duration adjustment and can thus be used to estimate the characteristics of the most efficient recovery step (i.e. the shortest and fastest step); two different hypotheses about CoM's evolution are considered and evaluated; two sets of parameters are proposed to represent the BR characteristics in the anterior direction of young and elderly healthy subjects and are used to assess model performances against human data from the literature.

2. Method

2.1. Experimental data

In this study we chose to reuse experimental data from the literature. Three different relevant studies are selected as they provide sufficient information about 1-Step BR experiments for both young and elderly subjects (e.g. thresholds, step length, step timings) but also as they used different types of perturbation or BR instructions. Hsiao-Wecksler and Robinovitch (2007) determined the 1-Step BR threshold in tether released experiments for different constraints on the recovery step length: limited at 15%, 25% and 35% of subject body height or unconstrained. BR reactions are supposed to be at their maximal performances. The study from Thelen et al. (1997) also used tether release experiments. They imposed a recovery in one step but did not put constraints on the step length. They tested different release angles, up to the 1-Step BR threshold. BR reactions before the maximal release angle are thus considered sub-maximal. Moglo and Smeesters (2006) used several type of postural perturbations (tether release, tether release+waist pull and waist pull during walk) in order to establish the threshold line, in the plane of CoM's angular position and velocity at the onset of the reaction, that discriminated states that can be recovered in one step from those ones which cannot.

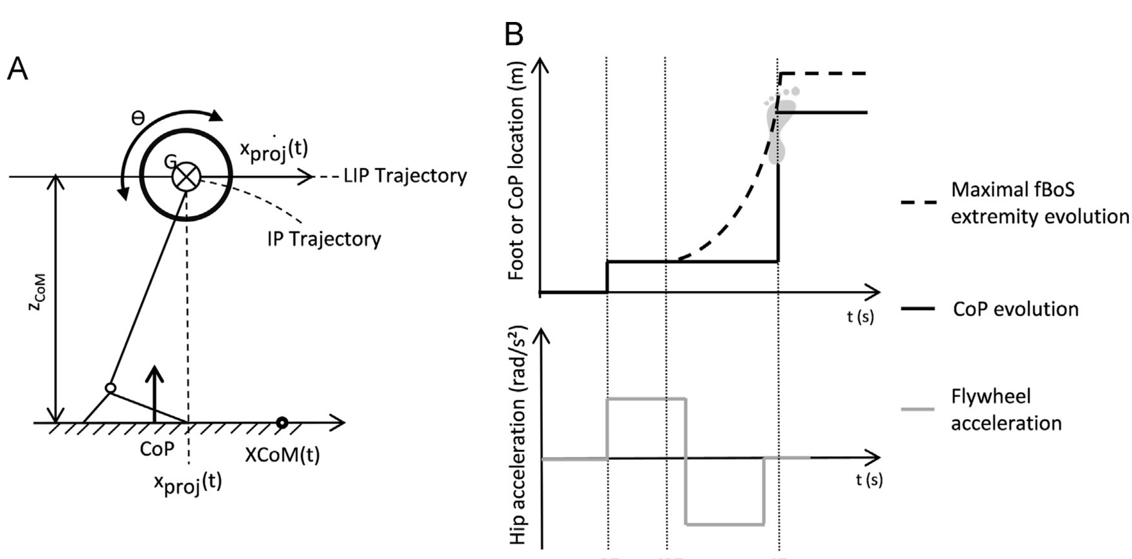

Fig. 1. (A) Representation of the IP and LIP model used in this study. (B) Maximal use of the three recovery strategies. No strategies are used from 0 to Reaction Time (RT). Ankle strategy, represented by the CoP evolution (black line), is launched at RT with a shift toward the fBoS extremity. Hip strategy is also launched at RT with the beginning of the bang–bang flywheel acceleration profile (gray line). The swing phase of a recovery step starts after an additional delay (Step Preparation Time, SPT). The furthest location of this recovery step is defined by a polynomial expression (see in the text) and represented as the black dashed line. Step Time (ST) corresponds to the recovery step landing. At this instant (gray footprint), the CoP is instantaneously shifted toward the new edge of the fBoS.

Table 1
Definition of two sets of balance recovery parameters for young and elderly population. Values from the first part of the table were chosen at the middle of the ranges of the experimental data reported in the three studies considered.

	Young value[a]	Elderly value[a]	References
Reaction time (s)	70 (56–101)	80 (71–96)	Thelen et al. (1997); Hsiao-Wecksler and Robinovitch (2007); Moglo and Smeesters (2006)
Step preparation time (s)	160 (129–200)	180 (135–213)	
Max foot acceleration (m/s^2)	165 (100–239)	145 (100–205)	
Max step length (% body height)	65 (63–69)	55 (44–54)	
Functional Base of Support (% BoS)	60	42	King et al. (1994)
IW inertia (kg m^2)	8	8	Aftab et al. (2012)
Maximal IW torque (N m)	150	150	
Maximal IW rotation (rad)	$\pi/4$	$\pi/4$	
Maximal lean angle (rad)	$\pi/3$	$\pi/3$	–

[a] When present, values in brackets are the ranges of the experimental data reported in the three studies considered.

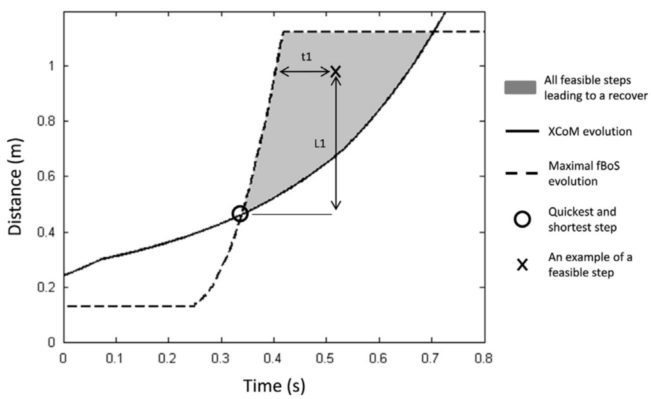

Fig. 2. Illustration of the model's principle. An example of XCoM evolution (black line) vs. the maximal BoS edge location (Black dotted line) is displayed. The first intersection between these two curves (black circle) indicates the quickest and shortest step (where and when the BoS extremity has to be located) leading to a recovery in one step. All steps which are located beyond the XCoM curve and below the maximal BoS location can also lead to a recovery in one step (gray area) and are considered sub-maximal. Steps beyond the dotted line are physically unfeasible and steps below the XCoM curve do not lead to a recover in one step. An example of sub-maximal step is given by the black cross (X). For this step L1 is the distance between the optimal step and the experimental step. t1 is the step landing time difference between the experimental step and its length equivalent step taken from the maximal step evolution. These two variables could be analyzed to characterize the BR (see Section 4).

2.2. Balance recovery model

2.2.1. Mechanical model

The human body is represented as an IP or a LIP with a concentered mass at the CoM linked to a massless foot and a flywheel centered at the CoM (see Fig. 1, left panel). The IP model follows a circle around the ankle joint whereas the LIP model remains at a constant altitude (z_{CoM}).

The XCoM is computed according to Eq. (1), where x_{proj} and $\dot{x}_{proj}$ are the position and velocity of the projection of the CoM on the ground, z its altitude and g the gravity (Hof et al., 2005)

$$\mathrm{XCoM}(t) = x_{proj}(t) + \frac{\dot{x}_{proj}(t)}{\omega_0}, \quad \omega_0 = \sqrt{\frac{g}{z}} \tag{1}$$

2.2.2. Balance recovery reactions

The literature defines three main strategies to recover balance (Horak and Nashner, 1986; Maki and McIlroy, 1997). These three strategies and their mechanical effects are respectively controlled thanks to three control variables:

Ankle strategy: the position of the Center of Pressure (CoP) can be shifted within the functional Base of Support (fBoS) (King et al., 1994).
Hip strategy: the FW can be accelerated around the CoM in order to represent the angular momentum generated by the rotation of the body segments (e.g. arms and trunk during the hip strategy).
Stepping strategy: the recovery step is represented by an extension of the BoS at the time of the step landing.

Given an initial perturbed situation, the possibility of restoring a standing equilibrium is estimated by considering that the person uses the most efficient recovery reactions. These are modeled as follow (see Fig. 1, right panel): after a Reaction Time (RT), the CoP is instantaneously shifted toward the edge of the fBoS. At the same time the FW is launched by following a bang–bang acceleration profile limited by the maximal acceleration/deceleration and the maximal rotation angle (Pratt et al., 2006). The swing phase of the recovery step starts after an additional delay named Step Preparation Time (SPT) representing the postural adjustments needed to trigger the step. The temporal profile of the swing foot horizontal displacement is defined by a 5th order polynomial, to ensure the continuity of the acceleration profile, with null velocity and acceleration at take-off and landing (Aftab et al., 2012). The swing foot displacement is thus bounded, at each instant of the swing phase, by the maximal acceleration of the swing foot and, if reached, by the maximal step length.

2.2.3. Model parameters

Our model has two types of parameters. The first type is used to describe the tested situation, mainly the subjects' anthropometry and the applied perturbation. The second type of parameter is used to describe the constraints that limit the BR, in particular the BR reactions. Two different sets of BR parameters are proposed in this study (see Table 1), for asymptomatic young and elderly subjects respectively.

Reaction time and maximal step characteristics reported in the three studies considered have been averaged to get the parameters reported in Table 1. Although the maximum foot acceleration was not explicitly reported it was estimated from the step length and swing foot duration according to the hypothesis made on the swing foot displacement time profile. In a first approximation, the FW limits were estimated from biomechanical limits on the trunk rotation (Chaffin et al. 2006). Due to the lack of reference data, we chose not to adjust the parameters related to the FW between young and elderly groups. The maximal lean angle was used to prevent unrealistic situations. This parameter is only needed for the IP model and the choice of its value is discussed in the Appendix A.

2.2.4. Estimation of the possibility to restore balance

Starting from the initial state, we estimated the evolution of the IP or LIP mechanical model due to gravity, the maximal "ankle" and "hip" reactions described above and possibly other external perturbations (e.g. pull force) by solving the equations of motion

Table 2
Experimental situations tested with our model.

	Subjects' characteristics		Initial state		Constraints on BR steps	Outputs
	Young	Elderly	Angle	Velocity		
Thelen et al., 1997	10 M (24 yrs) 1.73 m, 73 kg	10 M (71 yrs) 1.77 m, 75 kg	Imposed[a]	0	Subject's max[b]	Step charact. (sub-threshold)
			Variable	0	Subject's max[b]	Angle threshold Step charact. (threshold)
Hsiao-Wecksler & Robinovitch, 2007	10 F (28 yrs) 1.63 m, 62 kg	10 F (75 yrs) 1.57 m, 65 kg	Variable	0	Imposed[c]	Angle threshold Step timing (threshold)
			Variable	0	Subject's max[b]	Angle threshold Step charact. (threshold)
Moglo and Smeesters, 2006	5M–5W (23 yrs) 1.73 m, 71 kg	5M–5F (67 yrs) 1.66 m, 69 kg	Variable[d]	Variable[c]	Subject's max[b]	Angle threshold for ≠ init. vel.[d]

[a] From 15% to 55% of body height (increments of 5%).
[b] See Table 1.
[c] 15%, 25% and 35% of body height.
[d] State at RT

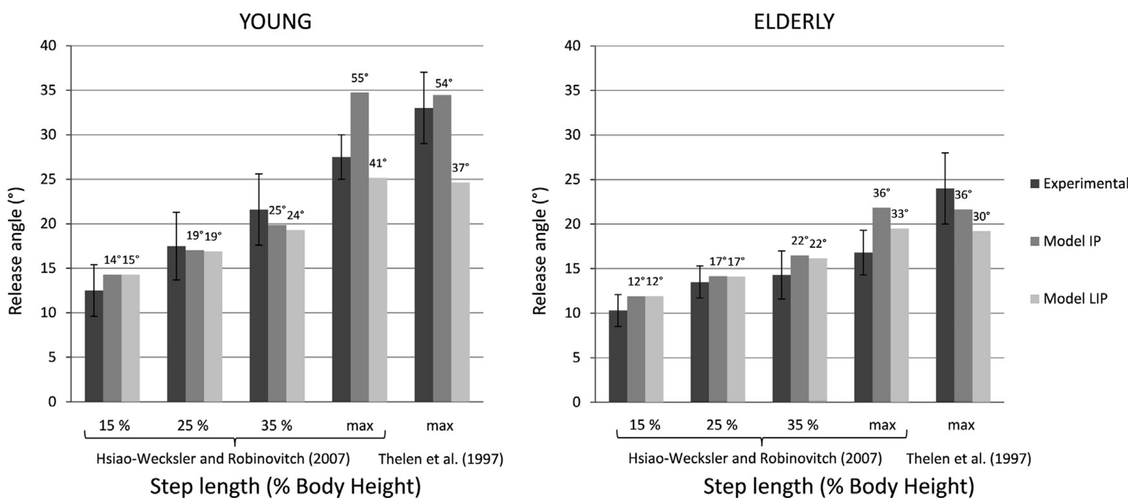

Fig. 3. Maximal release angles sustainable with a single recovery step as estimated by our models (IP and LIP) and experimental results from Hsiao-Weckler and Robinovitch (2007) and Thelen et al. (1997) for young subject (left panel) and elderly subjects (right panel). Anthropometry differences between the two experimental studies create different model results at the maximal step length. Angles displayed at the top of each model results represent the angle of the CoM forward inclination at step landing.

system (see Appendix B). The XCoM was then computed using Eq. (1). In parallel, at each time discretization the furthest location of the edge of the fBoS was computed by considering the longest possible recovery step.

An intersection between these two curves indicates that there is at least one recovery step that captures the XCoM (see Fig. 2). The tested situation is thus considered as recoverable and the intersection point defines the fastest and shortest recovery step. If no intersection exists the model cannot capture the XCoM and this situation leads inevitably to a fall if no more than one recovery step is taken.

2.3. Assessment against experimental data

The model was tested in the different situations from the three experimental studies considered. Only two sets of parameters describing the BR reactions were used for all these tests: one for the young subjects and one for the elderly (see Table 1). For each study, the model anthropometrical parameters (altitude of the CoM and size of the BoS) were estimated from the average stature of the group of subjects considered using regression from Winter (2009). Additional experimental constraints, such as the maximal step length or the release angle, were also considered. Table 2 summarizes the different tested configurations. The model outputs in particular the 1-Step BR threshold and the BR step characteristics were then compared to the experimental values.

3. Results

Fig. 3 shows the predicted vs. experimental 1-Step BR thresholds for the tether release situations (Hsiao-Weckler and Robinovitch, 2007 and Thelen et al., 1997). Overall the predicted thresholds for both IP and LIP model matched well the experimental observations. Differences between experimental and predicted thresholds were below 3° and within the experimental standard deviation, except for two cases in the unconstrained step situations (last case from Hsiao-Weckler and Robinovitch (2007) for the IP and threshold case from Thelen et al. (1997) for the LIP), where errors are between 4° and 8° (i.e. between 1° and 5° outside of the experimental standard deviation).

Thresholds predicted with the IP and LIP models are very similar for smaller perturbations (the three fixed step length scenarios from Hsiao-Weckler and Robinovitch (2007)). However, differences between the IP and LIP model appear for larger perturbations, i.e. for larger lean angles at step time (see Fig. 3), for which LIP thresholds get smaller than IP thresholds.

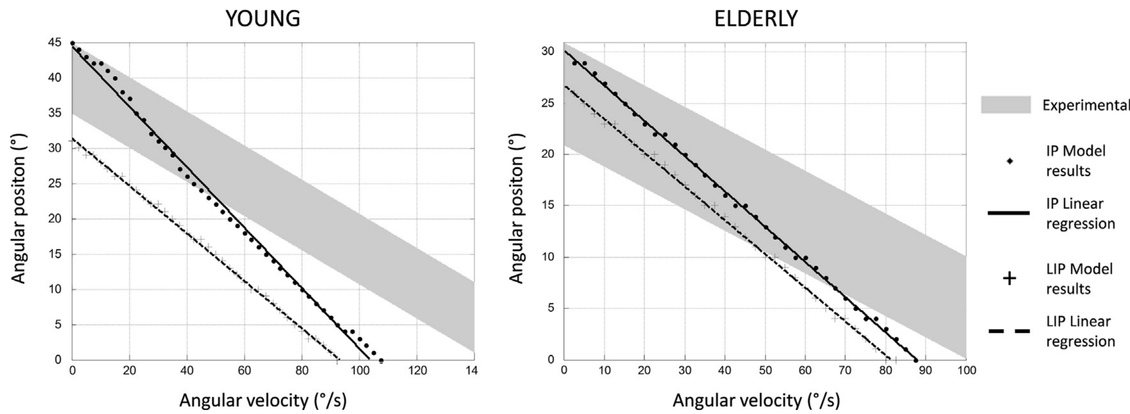

Fig. 4. Comparison between experimental (gray) vs. simulated (black) 1-Step BR thresholds in term of COM state at reaction time for young (left panel) and elderly (right panel) subjects. Gray area represents the experimental results (average plus or minus one standard deviation) from Moglo and Smeesters (2006). Black dots are the thresholds obtained with the IP model (maximal recoverable angular position at TR for a given angular velocity). The black line is the linear regression of these points (R^2=0.99). Crosses are the thresholds obtained with the LIP model. The black dotted line is the linear regression of these points (R^2=0.99).

Table 3
Experimental vs. IP and LIP model main results for tether release threshold situations: four situations from Hsiao-Wecksler and Robinovicth (2007) and threshold situation for Thelen et al. (1997).

		Young					Elderly				
		Hsiao-Wecksler[a]				Thelen[b]	Hsiao-Wecksler [a]				Thelen[b]
		15%	25%	35%	Max	Max	15%	25%	35%	Max	Max
Step length (cm)	*Exp.*	*29 (2)*	*46 (2)*	*62 (3)*	*103 (10)*	*117 (–)*	*27 (3)*	*41 (3)*	*57 (5)*	*69 (8)*	*88 (–)*
	IP Model	24	41	57	106	113	24	39	56	86	97
	LIP Model	24	41	57	106	113	24	39	56	86	97
Step time (ms)	*Exp*	*320 (30)*	*350 (30)*	*380 (20)*	*440 (40)*	*450 (–)*	*390 (60)*	*410 (40)*	*480 (60)*	*490 (30)*	*480 (–)*
	IP Model	300	330	360	410	420	340	370	400	440	450
	LIP Model	300	330	360	410	420	340	370	400	440	450
Release angle threshold (deg)	*Exp*	*12.5 (2.9)*	*17.5 (3.8)*	*21.6 (4)*	*27.5 (2.5)*	*33.0 (4)*	*10.3 (1.8)*	*13.5 (1.8)*	*14.3 (2.7)*	*16.8 (2.5)*	*24.0 (4)*
	IP Model	14.3	17	19.9	34.7	34.5	11.9	14.2	16.5	21.8	21.7
	LIP Model	14.2	16.7	19.3	25.2	24.6	11.9	14.1	16.1	19.5	19.2
Lean angle at step landing (deg)	*Exp*	–	–	–	–	–	–	–	–	–	–
	IP Model	14	19	25	55	54	12	17	22	36	36
	LIP Model	15	19	24	41	37	12	17	22	33	30

Data in brackets are experimental standard deviations; data in gray were constrained by the instructions.
[a] Hsiao-Wecksler and Robinovitch (2007).
[b] Thelen et al. (1997).

Regarding other perturbations (tether-release, tether-release+waist-pull and waist-pull+walking), comparison with results from Moglo and Smeesters (2006) is displayed in Fig. 4. The predicted threshold lines for both IP and LIP are almost linear (R^2=0.99), similar to what was experimentally observed. Predicted thresholds for the IP matched well the experimental observations for the lower initial velocities. The predicted thresholds are lower than the experimental ones for higher velocities (i.e. greater than 35°/s for young and 45°/s for elderly). It results in a steeper predicted threshold line than the experimental one. Again, the LIP model provides lower thresholds than the IP over the whole range of initial velocity.

Recovery step timing adjustment for different thresholds situations can be seen in Table 3. Step timings predicted by the IP model are in agreement with the experimental data. In particular both tend to increase with the maximal step length allowed. Step characteristics observed for perturbation thresholds are close to the most efficient (shortest and fastest) recovery step predicted by our model. For the IP model, the mean errors for the five threshold perturbations tested are below 5 cm and 50 ms. However, for sub-threshold cases from Thelen et al. (1997), predicted steps are faster and shorter than the experimental ones (see Fig. 5). This difference decreases as the perturbation gets closer to the maximal recoverable perturbation. One can remark that the step length and the step timing at the perturbation threshold are equivalent between the IP and LIP models. This fact is discussed in Appendix C.

4. Discussion

Two different models of CoM evolution before the BR step landing were considered in this study: an inverted pendulum (IP) vs. its linearized version (LIP). In terms of BR thresholds, results obtained with these two models were very similar for lower perturbations. However, IP thresholds became larger than LIP thresholds for stronger perturbations (cf. Fig. 3), i.e. for large angular displacements of the CoM (see Table 3). This can be explained by the fact that the XCoM is computed from the horizontal components of the CoM's displacement and velocity. These values are similar between IP and LIP for smaller angles. However, as angles get larger, these values keep diverging exponentially for the LIP while they converge towards bounds for the IP (leg length and null horizontal velocity component for a 90° inclination). At large angles the XCoM is then closer to the CoP in the IP case than in the LIP case. It leads to higher thresholds for the IP model. Overall, both models could be used interchangeably to estimate the BR thresholds in the case of low perturbations, typically for frail populations or in the case of specific instructions limiting

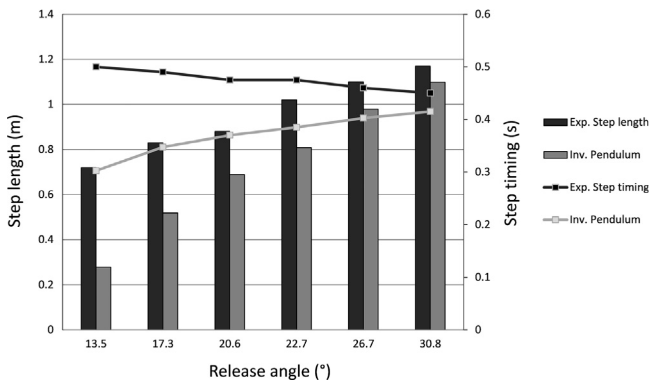

Fig. 5. Comparison between experimental recovery step characteristics (black) vs. those simulated with the IP (gray) for young subjects in the experimental situations from Thelen et al. (1997): step length (bars, left scale) and step time (dots, right scale). No standard deviations were given in this study for these results.

these thresholds, e.g. limiting the BR step length as in Hsiao-Wecksler and Robinovitch (2007).

Our model includes explicit constraints on the maximal step length as a function of time since RT. As such, it can be used to predict the fastest and shortest step that can lead to a recovery. These predictions are in agreement with the characteristics of the recovery step performed by subjects for scenarios close to the thresholds. However, for sub-threshold situations, subjects tended to perform longer and slower steps as highlighted in Fig. 5. This strategy likely minimizes the energetic cost of performing a very quick step. Longer steps than necessary also indicate that subjects tend to take a safety margin in order to face higher perturbations than anticipated or potential misplacements of the foot. It could be interesting to analyze the step characteristics relative to the set of acceptable recovery steps (gray area in Fig. 2), e.g. the length difference between the step performed and the shortest step that leads to a recovery (L1 in Fig. 2) or the delay between the actual step landing and the equivalent step under maximal performances which could have led to a balance recovery (t1 in Fig. 2). These variables should be only considered if the subject's capacities are characteristics of the population group considered in the model (individual results are compared to the performances of an average model). Nevertheless, these variables could bring useful insights into the BR neuromuscular mechanisms, similar to the Margin of Stability (MoS – distance between XCoM and edge of the BoS) (Arampatzis et al., 2008; Mademli et al., 2008; Barrett et al., 2012). Moreover, their assessment requires only little experimental effort and thus could thus be easily used in a clinical setting: only the step length and timing measurement is needed, while assessing the MoS requires a much more complex estimation of the CoM displacement.

The proposed model and the two sets of BR parameters allowed a relatively good estimation of the 1-Step BR thresholds in the anterior position for different populations, perturbations and BR instructions. Predicted tether release angle thresholds were within the experimental variability for all fixed step configurations. For unconstrained step length situations, both models performed well for one study but not the other (the IP for Thelen et al. (1997) and the LIP for Hsiao-Wecksler and Robinovitch (2007)). Further experiments should be performed in order to clarify these contradictory results. Compared to the results from Moglo and Smeesters (2006) our model correctly predicted the BR thresholds for the lower CoM velocities. However, predicted slope is steeper than the experimental one due to lower predicted thresholds for higher CoM velocities. This may come from the discrepancies in the initial state between our model and the experiments for the highest initial velocities. Subjects from Moglo and Smeesters (2006) were initially walking at the time of perturbation, i.e. the recovery steps were likely already initiated at the end of the RT. On the contrary, our model includes a delay (the SPT) between the end of the RT and the initiation of the swing phase. This additional delay increases the time to perform a recovery step and consequently reduces the ability to recover from larger perturbations.

In this study we chose to assess our model against different experimental studies without adjusting the set of parameters describing the BR reactions (only the subject's stature, and by consequence the maximum step length, is adjusted). This choice could be discussed, as it neglected the differences in subjects' capacities between the three groups. For example, only male subjects were included by Thelen et al. (1997) vs. only females by Hsiao-Wecksler and Robinovitch (2007). It may explain the different performances of our model in regard of these two studies (see Fig. 3). However, the use of the same sets of parameters to predict BR thresholds for the different studies, instructions and test configurations allowed a stronger validation of the model principles. Moreover, these two sets of parameters represent one of the important outcomes of this study, as they make the model directly usable for studying BR for healthy young or healthy elderly subjects. In addition, as the model parameters were chosen to be as interpretable as possible, one can analyze deviations from these standard sets. For example, differences between young and elderly sets highlight an average ageing effect on the BR capacities (see Table 1). Differences can be summed-up by a longer step initiation (McIlroy and Maki, 1996; Tisserand et al., 2015) associated with a lower swing foot acceleration and lower maximal step length (deterioration of the capacity to perform long but quick recovery steps (McIlroy and Maki, 1993) for the elderly compared to the young. Analyzing the influence of the different BR reactions through a sensitivity analysis on the model parameters or by comparing model parameters adjusted to different populations would certainly give interesting insights into the neurophysiological parameters and mechanisms involved in the BR.

This model still has several limitations. Firstly, it has only been assessed in the anterior direction, mainly due to the lack of available experimental data. However, there are no conceptual obstacles preventing extension in other directions as shown in the work by Koolen et al. (2012) on a similar model. The main difficulty would be to adjust the BR parameters to the different perturbation/recovery directions. Similarly, the experimental situations considered in this study do not cover all of the classical perturbations, typically slips or trips during walking. The current model could be used to model these situations, although it is likely that the BR parameters should be adjusted.

Despite these limitations, the proposed model completes the current state of the art in terms of BR modeling. It is notably the first model allowing the 1-Step BR thresholds estimation that has been carefully assessed against human data. This model has thus a lot of potential in the field of fall prevention: not only it would be useful to detect situations at risk, but it could also be used to get important insights into the neurophysiological mechanisms involved in the BR process.

Conflict of interest statement

Authors have no conflict of interest to report in this research.

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Appendices. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2015.09.024.

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