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Center of Pressure Plausibility for the Double-Link Human Stance Model Under the Intermittent Control Paradigm

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Abstract

Despite human balance maintenance in quiet conditions could seem a trivial motor task, it is not. Recently, the human stance was described through a double link inverted pendulum (DIP) actively controlled at the ankle with an intermittent proportional (P) and derivative (D) control actions based on the sway of a virtual inverted pendulum (VIP) that links the ankle joint with the DIP center of mass. Such description, encompassing both the mechanical model and the intermittent control policy, was referred as the DIP/VIP human stance model, and it showed physiologically plausible kinematic patterns. In this study a mathematical formalization of the Center of pressure (COP) for a DIP structure was developed. Then, it was used in conjunction with an intermittently controlled DIP/VIP model to assess its kinetic plausibility. Three descriptors commonly employed in posturography were selected among six based on their capability to discriminate between young (Y) and elderly (O) adults groups. Then, they were applied to assess whether variations of the P-D parameters affect the synthetic COP. The results showed that DIP/VIP model can reproduce COP trajectories, showing characteristics similar to the Y and O groups.

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Moreover, it was observed that both P and D parameters increased passing from Y to O, indicating that the COP obtained from the DIP/VIP model is able to highlight differences in balance control between groups. The study hence promote the use of DIP/VIP in posturography, where inferential techniques can be applied to characterize neural control.

Keywords: Center of pressure, Upright stance modeling, Human balance maintenance, Intermittent control

Word count:

3493

1 1. Introduction

The study of the human stance received close attention over the years, from biomechanics to neuroscience and robotics (Collins & De Luca, 1993; Peterka, 2000; Popović, 2013), focusing on the comprehension on how the Central Nervous System (CNS) manages the sensory information and how it generates control commands to stabilize the body, eventually preventing falls. Indeed, as experimentally demonstrated, ankle stiffness is not sufficient to guarantee the upright stance stability *per se* (Morasso & Sanguineti, 2002). Thus, a CNS mediated action must come into play to actively support the passive stabilizing mechanisms (Casadio et al., 2005; Baratto et al., 2002; Morasso et al., 2019).

The modeling of the human balance maintenance can be thereby viewed as a 11 cybernetic problem, where the mechanics of the body affects and coexists with 12 the processes that CNS is engaged to solve, i.e. sensory information fusion, 13 motor commands generation and delivery (Morasso et al., 2019). Single-link (SIP) or double-link inverted (DIP) pendulum were commonly adopted to model 15 the body stance (Morasso et al., 2019; Asai et al., 2009; Suzuki et al., 2012; 16 Cenciarini et al., 2010), while the description of the neural controller is currently 17 a discussed topic (Morasso et al., 2019). Many authors approached the problem 18 through a continuous control paradigm, where proportional (P) and derivative 19 (D) controllers act upon a delayed information of the sway angle (Peterka, 2000). 20 This paradigm however presented some limitations, since it is highly sensitive 21 to the feedback loop delay, with poor robust performances. From the other side, 22 the idea that the CNS tunes the regulatory commands (Collins & De Luca, 1993) 23 was further developed and proposed under the variable structure control (VSC) 24 paradigm (Asai et al., 2009; Suzuki et al., 2012; Milton & Insperger, 2019). The 25 latter constitutes a physiologically plausible alternative to a continuous control: 26 through a VSC, the unstable sub-dynamics of the system can be stabilized 27

²⁸ switching opportunely among them (Asai et al., 2009).

The model proposed by (Morasso et al., 2019) seemed to present a valuable 29 synthesis of the human-balance maintenance. Indeed, the authors modeled the 30 stance through a DIP structure on the sagittal plane, while the neural controller 31 acts at the ankle with an intermittent control policy (Morasso et al., 2019; Asai 32 et al., 2009). The hip instead contributes passively to the stabilization by over-33 stiffening the upper trunk (Morasso et al., 2019). A crucial point was the idea 34 that CNS employs a delayed knowledge of the Center of Mass (COM) sway to 35 generate active motor commands, leading to the use of a virtual inverted pendulum (VIP) that links the ankle joint to the COM, computed by the position of 37 the DIP structure. Such model showed kinematic coordination patterns between the lower and the upper segments in line with those observed in human balanc-30 ing (Morasso et al., 2019; Aramaki et al., 2001), resembling actual COM sway. 40 However, no information was provided regarding the Center of Pressure (COP) 41 fluctuations, which together with the COM play a key role in any quiet balanc-42 ing task (Morasso, 2020). It should be emphasized that the COP time course 43 is a directly measurable quantity, while COM can be only estimated through 44 many possible procedures (Morasso et al., 1999; Cardarelli et al., 2019). Fur-45 ther, classical posturography recognizes COP as fundamental to extract useful 46 information regarding how CNS regulates the stance through the control torques 47 (Collins & De Luca, 1993; Baratto et al., 2002). COP accounts for the resultant 48 control actions exerted not only at the ankle joint but also at the hip. Thus, 49 a SIP model can provide only a limited mechanical description of the human 50 51 stance.

In this work, a mathematical formulation of COP in the anterior-posterior direction for the DIP model was derived. Then, it was used to assess the plausibility of the DIP/VIP model in reproducing human-like COP balancing patterns,

relying on a set of suitable metrics, which require only the anterior-posterior 55 component for their computation. The latter were selected using actual COP 56 data, as descriptive of the underlying mechanisms behind CNS posture regu-57 lation (Amoud et al., 2007; Yamamoto et al., 2015; Collins & De Luca, 1993). 58 The active controller parameters of the DIP/VIP were varied within a certain 59 range of values (Morasso et al., 2019). The simulated COP were compared, 60 according to the aforementioned metrics, with actual COP data belonging to 61 two populations, i.e. young and elderly adults, where clear differences in sway 62 patterns were expected. 63

64 2. Methods

65 2.1. Dataset presentation

Posturographic data of thirty healthy subjects from a public dataset were 66 used (Santos & Duarte, 2016), fifteen belonging to a healthy adults group, rep-67 resenting a young cohort (Y) with an age not greater than 36.9 years and fifteen 68 to an elderly group (O), presenting an age greater than 60.0 years. Data were 69 sampled at 100 Hz for 60 s and filtered at 10 Hz with a zero-phase second order 70 low-pass filter and detrended. Only the anterior-posterior component (AP) of 71 COP was considered for further analysis since the DIP/VIP model describes 72 upright posture in the sagittal plane. 73

74 2.2. DIP/VIP human upright stance model

The DIP/VIP model describes the human posture through a double link inverted pendulum (see figure 1). Its dynamic equations can be obtained by using the lagrangian formulation (Siciliano et al., 2010; Morasso et al., 2019). The two generalized coordinates q_1 and q_2 (see the appendix) represent the angles between the lower body segment and the vertical axis, and between the lower and upper body segments respectively.

Given
$$\mathbf{q} = \begin{bmatrix} q_1 & q_2 \end{bmatrix}^T$$
 one can obtain:

$$\begin{cases} \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \boldsymbol{\tau} \\ \boldsymbol{\tau} = \boldsymbol{\tau}_B + \boldsymbol{\tau}_S + \boldsymbol{\tau}_I + \boldsymbol{\tau}_N \end{cases}$$
(1)

where $\mathbf{M}(\mathbf{q})$, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$, $\mathbf{G}(\mathbf{q})$ are the inertia matrix, the generalized Coriolis term, and the gravity dependent torque respectively. The sum of the torques applied at the two joints is represented by $\boldsymbol{\tau}$. More specifically, $\boldsymbol{\tau}_B$ refers to the bias torque, generated by a reference tilt angle between the body and the vertical axis and set to zero (Morasso et al., 2019; Asai et al., 2009; Suzuki et al., 2012). The terms $\boldsymbol{\tau}_S$ and $\boldsymbol{\tau}_I$ refer to the stiffness and intermittent control respectively. The first one is due to the muscles mechanical properties, which passively contribute to the stabilization of the body. Thus, $\boldsymbol{\tau}_S$ was modeled by a proportional and derivative contributes, as highlighted in the following:

$$\boldsymbol{\tau}_{S} = \begin{bmatrix} K_{a}q_{1} + B_{a}\dot{q}_{1} \\ K_{h}q_{2} + B_{h}\dot{q}_{2} \end{bmatrix}$$
(2)

where K_a and K_h model the stiffness at the ankle and the hip. B_a and B_h account for the intrinsic damping properties of the muscles. Instead, τ_I models the active role of the CNS, since a pure passive mechanical component cannot stabilize human stance (Morasso & Sanguineti, 2002).

In the DIP/VIP modeling framework (Morasso et al., 2019), the novel aspect was to apply the intermittent control only at the ankle joint while the hip coupled the lower body segment passively with the upper trunk, contributing to the stabilization by means of τ_S . Thus, a key element is the use of the VIP model to generate active motor commands. Indeed, for any multi-link mechanical structure, one can obtain the position of the COM, i.e. $x_g(\mathbf{q})$ and $y_g(\mathbf{q})$ in figure 1 by computing its sway angle q_{COM} (Morasso et al., 2019). The active control τ_I can be computed following (Morasso et al., 2019; Asai et al., 2009):

$$\boldsymbol{\tau}_{I} = \begin{cases} \begin{bmatrix} -(P\delta q_{COM} + D\delta \dot{q}_{COM}) \\ 0 \end{bmatrix} & \text{if } \delta q_{COM} (\delta \dot{q}_{COM} - \alpha \delta q_{COM}) > 0 \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} & \text{otherwise} \end{cases}$$
(3)

where δq_{COM} indicates q_{COM} delayed by δ interval of time used to model neural 85 delay, fixed at $\delta = 0.2$ s (Morasso et al., 2019). The intermittent control law 86 applies a proportional and derivative actions at the ankle joint whether COM 87 leaves the stable manifold described by $\delta q_{COM} (\delta \dot{q}_{COM} - \alpha \delta q_{COM}) \leq 0$ (Asai 88 et al., 2009). Here $\alpha = 0.4 \text{ s}^{-1}$ was chosen (Morasso et al., 2019; Asai et al., 89 2009). Conversely, active control switches off when the system approaches or 90 remains in the stable manifold (Asai et al., 2009). Based on the results presented 91 in (Morasso et al., 2019), in this work P varied between 0.3 mgh and 0.9 mgh 92 N·m, and D between 0 to 200 $N \cdot m \cdot s/rad$ (Morasso et al., 2019). 93

As reported by (Suzuki et al., 2012; Conforto et al., 2001), quiet upright stance is challenged not only by the gravity field, but also by internal postural noise (Asai et al., 2009; Conforto et al., 2001), represented by τ_N , which acts independently at the two joints. τ_N was modeled as white noise, low-pass filtered at 10 Hz and having standard deviation of 0.2 N·m (Morasso et al., 2019; Suzuki et al., 2012).

100 2.3. COP formulation for the double link inverted pendulum

Despite the plausibility of DIP/VIP model was assessed in reproducing kinematic human-like sway patterns, no hint regarding the COP time evolution was given (Morasso et al., 2019). In the stance phase (see figure 1) the following equation holds (Chevallereau et al., 2008):

$$m\begin{bmatrix} \ddot{x}_g\\ \ddot{y}_g \end{bmatrix} + mg\begin{bmatrix} 0\\ 1 \end{bmatrix} = \mathbf{R} = \begin{bmatrix} R_x\\ R_y \end{bmatrix}$$
(4)

where m is the total mass of the subject, g is the gravity acceleration, and \mathbf{R} represents the ground reaction force with its two components R_x and R_y . The equilibrium of the DIP around the ankle joint axis can be obtained as:

$$\dot{\sigma}_a = mgx_g - COP(t)R_y - l_a R_x \tag{5}$$

where σ_a is the angular momentum of the DIP about the ankle, *COP* is the displacement of the center of pressure with respect to the ankle joint and l_a is the height of the latter with respect to the ground (see figure 1). By definition, σ_a is linear with respect to the joint velocities and can be written as reported in (Chevallereau et al., 2008):

$$\sigma_a = \frac{\partial}{\partial \dot{q}_1} \mathcal{L}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{N}(\mathbf{q}) \dot{\mathbf{q}}$$
(6)

 σ_a is a conjugate momentum that can be obtained by differentiating the Lagrangian $\mathcal{L}(\mathbf{q}, \dot{\mathbf{q}})$ of the system with respect to \dot{q}_1 . Such derivative can be rearranged as the scalar product between the vector field $\mathbf{N}(\mathbf{q})$ and the joint velocity vector $\dot{\mathbf{q}}$ (Westervelt et al., 2018) (appendix). Combining (4) and (5), it is possible to compute the COP for a DIP structure:

$$COP(t) = \frac{mgx_g - (\dot{\sigma}_a + ml_a \ddot{x}_g)}{m(\ddot{y}_g + g)}$$
(7)

Since the product of l_a and R_x in (5) can be profiled out (Schut et al., 2020), this finally leads to:

$$COP(t) = \frac{mgx_g - \dot{\sigma}_a}{m(\ddot{y}_g + g)} \tag{8}$$

101 2.4. COP parameters selection and model evaluation

Three COP descriptors were used to assess the kinetic plausibility of the 102 DIP/VIP model. Such descriptors were selected among a set of six, based on 103 their ability in underlining significant differences between the two populations 104 (Y and O). The initial feature set embraced the only two universal indexes in 105 AP direction presented in (Yamamoto et al., 2015): the frequency at which 106 COP presents the 50% (PF50) of its whole power spectrum density (PSD) (Ya-107 mamoto et al., 2015; Prieto et al., 1996), and the slope of the PSD in the low 108 frequency band 0.1 - 0.5 Hz (SLOPE-L) (Asai et al., 2009; Yamamoto et al., 109 2015). Also the critical time (T_{CR}) was included (Toosizadeh et al., 2015; Ya-110 mamoto et al., 2015; Novak et al., 2009), obtained as the time interval at which 111 the intersection between the two fitting lines on linear-scale stabilogram dif-112 fusion plot (SDP) occurs (Collins & De Luca, 1993). Finally, the generalized 113 Hurst exponent (HE), computed through detrended fluctuation analysis (DFA) 114 (Amoud et al., 2007; Srinivasan et al., 2012), was also considered, together with 115 two features related to sway amplitude, i.e. the mean distance (MD) and the 116 sway range (SR) (Prieto et al., 1996; Błaszczyk et al., 2007). For the DFA 117 computation the windows size ranged from 0.1 s (10 samples) and 10 s (1000 118 samples). Each feature was computed for both Y and O groups. Normality of 119 data distributions was tested through the Kolmogorov-Smirnov test. Compar-120 isons between groups were performed by ANOVA or Wilcoxon rank sum test for 121 gaussian or non-gaussian distributed data. For each test, statistical significance 122 was set at p < 0.05. 123



PF50, T_{CR} and HE resulted able to discriminate between Y and O groups

and thus used for the evaluation of COP time-series obtained as output of the 125 DIP/VIP. Such model was implemented in MATLAB/Simulink (The Mathworks 126 Inc.). The anthropometric characteristics required to fill the model were com-127 puted as the average among the subjects (appendix). The ranges of values for P 128 and D parameters (section 2.2) were linearly spaced forming a parameter space 129 and used to parametrize the intermittent controller for the simulation of COP 130 from the DIP/VIP model. P-D grids representation was limited to those values 131 for which the model provided stable and physiologically plausible outputs. For 132 each combination of P-D parameters, 10 COP time-series were generated. 133

Then, PF50, T_{CR} and HE were computed for each COP, providing the 134 dependency of each metric upon P and D combinations. For both groups, it 135 was assumed a plausible range for each considered metric (PMR), defined as the 136 mean population value \pm standard deviation (Table 1). Eventually, a series of 137 grids was built to obtain P and D ranges for which all the three COP descriptors 138 were coherent with synthetic and real data at the same time. Therefore, those 139 P-D values for which the feature maps fell within the PMR-Y and PMR-O at 140 least one time among the ten COP realizations and for all of the three features 141 were selected. 142

143 3. Results

The average PSD, represented in a log-log scale (figure 2a) shows a higher power content at the lower frequencies for the Y group and a statistically significant lower PF50 (figure 2b), as confirmed also by the PMR (Table 1).

For Y population, the mean SDP (figure 2c) increased less than the elderly at the lower time scales. This contributes to the higher T_{CR} (Table 1), since the SDP slope in its first part heavily impacts on the T_{CR} estimation (Collins & De Luca, 1993). The statistical analysis (figure 2d) showed significant differences ¹⁵¹ between the groups.

Eventually, the HE exhibited a strong significant difference between the two 152 groups (figure 2f), confirming the discriminant power of this feature (Amoud 153 et al., 2007). This can be appreciated also from the remarkable change in the 154 average regression lines slope between Y and O groups (figure 2e and Table 1). 155 The three COP descriptors were also computed for the synthetic COP data. 156 Gray-maps (figure 3) describe how PF50, T_{CR} and HE vary with respect to 157 the active control parameterization. PF50 seems to be more sensitive to the 158 variations of D when P was $\approx 300 \text{ N}\cdot\text{m/rad}$ (figure 3a), and greater PF50 159 excursions were found for low P values. On the opposite, T_{CR} (figure 3b) seemed 160 to better mirror changes in the P parameter when D was low (between 0 and 50 161 N·m·s/rad). The HE instead presented a smoothed trend, radially decreasing 162 when both P and D increase (figure 3c). Eventually, the ranges obtained for 163 the two groups were reported in table 2 and their average \pm standard deviation 164 values are reported as shaded areas in figure 3. Larger P and D values were 165 admissible to obtain COP having characteristics in line with the O group with 166 respect to the Y population. On the contrary, the Y group admitted narrower 167 P and D ranges. 168

		PMR		
Group	$\mathbf{PF50}$	T_{CR}	HE	
	(Hz)	(s)		
Y	$0.09{\pm}0.06$	$1.63 {\pm} 0.59$	$1.32 {\pm} 0.12$	
Ο	$0.16{\pm}0.13$	$1.12{\pm}0.32$	$1.17 {\pm} 0.13$	

Table 1: Table shows PMR for the three parameters and for both populations.

Gr	oup	Р	D	
		$(N \cdot m/rad)$	$(N \cdot m \cdot s/rad)$	
	Y	$257.36 \div 322.38$	$0{\div}49.47$	
	0	$257.36 \div 463.25$	$0{\div}74.21$	

Table 2: Table shows the considered P and D ranges for the grids.

169 4. Discussion

The P-D grids (figure 3) seemed to confirm not only the sensitivity of synthetic COP to different parameterizations of the active controller, but also the possibility to obtain time-series whose descriptors lie within the PMR observed in the Y and O groups. This supports the goodness of the DIP/VIP model for the description of the human stance from a kinetic perspective, in addition to the kinematic one (Morasso et al., 2019).

Further, both P and D admitted greater values for the O group compared 176 to the Y one (Table 2). This might indicate the well known functional rear-177 rangement of the CNS control recognized in the elderly (Allum et al., 2002; 178 Collins et al., 1995), which can be mapped through the tuning of the intermit-179 tent controller and mirrored by the COP. In passing, greater P and D values 180 were associated with lower HE in the O group (figure 3c). This aspect high-181 lights an enhanced anti-persistent behavior of the elderly, aligning with (Amoud 182 et al., 2007; Collins et al., 1995) and indicating that greater regulatory efforts 183 are needed to achieve stability (Collins et al., 1995), resulting in a more ener-184 getically expensive control (Asai et al., 2009). 185

Regarding the PF50, it quantifies the spreading of the COP spectrum towards the higher frequencies, i.e. the greater is the PF50, the larger is the amount of power of faster dynamics, possibly associated with an augmented level of stochasticity (Yamamoto et al., 2015; Collins & De Luca, 1993). Since

COP encompasses control torques at the lower limbs joints, it undoubtedly re-190 flects also motor commands modulated by muscles activity and their mechanical 191 characteristics (Baratto et al., 2002). Therefore, an enhanced stochastic COP 192 behavior might refer to a "stiffer" muscular strategy, recognizable in the elderly 193 (Collins et al., 1995) and associated either to mechanical muscles properties or 194 to neuromodulatory changes. A global sign of this phenomenon can be found 195 in the PSD slope at the lower frequencies (SLOPE-L) (Yamamoto et al., 2015; 196 Suzuki et al., 2020; Asai et al., 2009): a nearly flat slope points out a body stiff-197 ness which tends to be overcritical, i.e. $\gg mgh$, while a negative value stands 198 for an optimal stiffness tuning and thus an efficient regulation (Suzuki et al., 199 2020; Asai et al., 2009). The former case was associated to a continuous control 200 with higher gains (Asai et al., 2009), while the latter takes advantages from a 201 VSC policy to achieve the global stabilization, admitting lower control gains, 202 resembling a physiological plausible dynamic (Morasso et al., 2019; Suzuki et al., 203 2020). This agrees with the greater P values for the O population and is also 204 supported by the SLOPE-L computed on the real data of both groups: as ex-205 pected they resulted higher for the O subjects (-0.95 ± 0.84) with respect to the 206 Y ones (-1.62 ± 1.15) . 207

Eventually, the T_{CR} appears less sensitive to changes in the P-D parame-208 ters. From the grids (figure 3b) it is easy to appreciate that T_{CR} has a uniform 209 trend and limited variations for a large set of the controller parameterizations. 210 This aspect is not completely surprising. Despite the DIP/VIP represents a 211 highly descriptive model of the human stance, it naturally incorporates some 212 approximations. Thus, the T_{CR} and the SDP appear able to highlight subtle 213 properties of balance, which might not be necessarily exploited by a mechanistic 214 model, whenever accurate (Baratto et al., 2002). In addition, the SDP repre-215 sents a conceptual framework for analyzing sway data, grounded on a timeseries 216

perspective rather than on a biomechanical modeling of the system generating 217 COP data (Collins & De Luca, 1993; Baratto et al., 2002). Thus, the role of the 218 T_{CR} in describing VSC models of posture deserves to be further investigated, 219 since it showed to be highly descriptive of different control dynamics exhibited in 220 both healthy individuals and populations presenting a wide spectrum of balance 221 disorders (Toosizadeh et al., 2015; Novak et al., 2009). Note that the choice of a 222 set of COP features already successfully used for investigating COP timeseries 223 in young and elderly subjects (Amoud et al., 2007; Collins et al., 1995; Prieto 224 et al., 1996) further supports the validity of the DIP/VIP model from a kinetic 225 viewpoint. Eventually, it deserves to be mentioned that the active controller 226 parameters investigation was limited to P and D gains, while α was set at a 227 fixed value (Section 2.2). This could represent a partial limitation of the study, 228 since the exploration of α in conjunction with P and D would add significant 229 information regarding the model and thus it needs to be adequately examined 230 in focused studies. 231

Modern posturography highlighted the tendency to infer active controller 232 parameters to underline differences among many populations or to identify a 233 model for each subject (Suzuki et al., 2020; McKee & Neale, 2019). This is 234 commonly achieved using data or features derived from COM, even if COP 235 measures were the most common data used in classical posturography (Morasso 236 et al., 2019; Suzuki et al., 2012; Morasso, 2020). However, at least a couple of 237 aspects suggest the opportunity to use COP rather than COM. Firstly, COP is a 238 directly measurable quantity, while the COM can only be estimated in a variety 239 of different ways, including the direct computation from COP, which results into 240 a smoothed version of the latter (Morasso et al., 1999; Eng & Winter, 1993). 241 Despite such procedures are commonly employed to highlight kinesiological fea-242 tures of balance, they could lead to a loss of information, that can be instead 243

captured through different identification approaches (Suzuki et al., 2020; Cor-244 radini et al., 1997). Indeed, the COP trajectory represents a meaningful source 245 of information regarding both the descending neural control and the mechan-246 ical actuation provided by the musculoskeletal system (Baratto et al., 2002), 247 appearing a more preferable choice when human stance is investigated from a 248 neuromuscular perspective. However, the use of a multi-link structure renders 249 more challenging the COP modeling, while defining COP from a single-link in-250 verted pendulum is quite straightforward (Schut et al., 2020). In this view, 251 the relation (8) (section 2.3) can be employed for double-link models. Thus, 252 despite the identification was not the aim of this study, the COP formulation 253 here developed represents itself a valuable contribution toward the integration of 254 physiological data and mechanical models of balance, since the latter provide a 255 high interpretability of its parameters, which can be linked to specific properties 256 of the neuromuscular system. 257

The additional value of using a DIP/VIP or in general a multi-link model 258 can be appreciated also considering that this allows to investigate if changes in 259 neural control are reflected in how CNS manages the intrinsic body redundancy 260 of the quiet stance (Suzuki et al., 2012; Reimann & Schöner, 2017). Indeed, a 261 loss of the CNS capacity in efficiently managing the redundancy can be a sign 262 of a functional rearrangement due to neurological disorders (Corradini et al., 263 1997). The central role of COP in accounting for mechanical redundancy is 264 fundamental also in other applications, e.g. bipedal legged robotics. In this 265 context, the COP and more in general the zero moment point has to encompass 266 the multi-link structure in its formulation, in order to properly control both 267 the standing and dynamic phases of gait (Chevallereau et al., 2008; Westervelt 268 et al., 2018). Therefore, an inefficient regulatory activity can be mirrored, and 269 thus recognized, by considering COP characteristics (Peterka, 2009). This could 270

²⁷¹ hold also for the human system, where a degraded regulatory activity, due to
²⁷² disease, can affect the multi-link structure management in balance maintenance,
²⁷³ which is *per se* a redundant motor task (Reimann & Schöner, 2017).

These aspects support the findings of Morasso et al. (2019), enriched in this 274 study by the kinetic perspective. Present results highlight the suitability of 275 modeling balance through a DIP structure, where VSC accounts for the CNS 276 role. The hybrid policy is employed for managing the body redundancy through 277 the VIP part of the model and resulted to drive synthetic COP characteristics. 278 Indeed, since a physiological coherent model of the control action at the two 279 joints was employed, human-like patterns were observed in the simulated COP 280 time-series. As emerged from (8) and (17), COP spans non linearly the torque 281 vector $\boldsymbol{\tau}$ over σ_a . Thus, both passive and active effects at the hip and ankle 282 were mirrored in the COP, which lumps the information about the stability of 283 the structure. 284

A further consideration regards the importance of a proper COP modeling, 285 since COP can be used as a feedback information in the balance control loop 286 (Peterka, 2009), rendering the system robust with respect to external perturba-287 tions, e.g. support base movements or external impacts (Peterka, 2009; Prahlad 288 et al., 2008). Note that also quiet stance undergoes internal and external distur-289 bance (Conforto et al., 2001; Nomura et al., 2013) and thus COP represents itself 290 a valuable source of information that can be used by the CNS for tuning bal-291 ance control strategies in either perturbed or unperturbed conditions. Despite 292 one can wonder about the existence of an internal model of the COP within 293 the CNS (Morasso et al., 2019), there is no doubt regarding the existence of 294 an integration process of tactile and proprioceptive sensors of the feet (Viseux, 295 2020), that makes plausible the existence of COP information within the balance 296 control schemes (Morasso et al., 2019). This suggests a more profound picture 297

regarding the nature of the COP. Indeed, as for certain balancing tasks, CNS 298 must switch the role between COP and COM information in the motor control 299 paradigm (Morasso, 2020). Thus, although classical literature (Winter, 2009) 300 agreed in viewing the COM as the controlled variable and COP as the control 301 variable, it could be a limiting assumption for studying possible rearrangements 302 in the motor control with respect to neurological disorders. This aspect can be 303 further investigated in future studies, where kinematic and kinetic simultaneous 304 measures are available (Santos & Duarte, 2016), in order to better clarify the 305 relationship between COP and COM in this kind of modeling framework. 306

307 Appendix

In this section further details regarding the dynamical equation (1), as well as a clarification on the conjugate momentum presented in (6) are shown. Consider the double-link inverted pendulum given in figure 1. By means of Lagrangian formulation, one can easily obtain the matrices required in (1) (Siciliano et al., 2010; Morasso et al., 2019). In particular:

$$\mathbf{M}(\mathbf{q}) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$
(9)

$$\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & 0 \end{bmatrix}$$
(10)

$$\mathbf{G}(\mathbf{q}) = -g \begin{bmatrix} G_1 \\ G_2 \end{bmatrix} \tag{11}$$

where

$$\begin{cases}
M_{11} = I_1 + I_2 + m_1 l_1^2 + m_2 (L^2 + l_2^2 + 2L l_2 \cos q_2) \\
M_{12} = M_{21} = I_2 + m_2 (l_2^2 + L l_2 \cos q_2) \\
M_{22} = I_2 + m_2 l_2^2
\end{cases}$$
(12)

$$\begin{cases} C_{11} = -m_2 L l_2 \dot{q}_2 \sin q_2 \\ C_{12} = -m_2 L l_2 (\dot{q}_1 + \dot{q}_2) \sin q_2 \\ C_{21} = m_2 L l_2 \dot{q}_2 \sin q_2 \end{cases}$$
(13)

$$\begin{cases}
G_1 = (m_1 l_1 + m_2 L) \sin q 1 + m_2 l_2 \sin(q_1 + q_2) \\
G_2 = m_2 l_2 \sin(q_1 + q_2)
\end{cases}$$
(14)

Regarding the conjugate momentum of the DIP with respect to the ankle joint σ_a (equation (6)), it can be obtained differentiating the Lagrangian with respect to the generalized velocity \dot{q}_1 . Consider the Lagrangian of the mechanical system:

$$\mathcal{L}(\mathbf{q}, \dot{\mathbf{q}}) \coloneqq \mathcal{K}(\mathbf{q}, \dot{\mathbf{q}}) - \mathcal{V}(\mathbf{q})$$
(15)

where the first two terms express the total kinetic and potential energy of the system, respectively (Siciliano et al., 2010; Westervelt et al., 2018). Then, one can observe that only $\mathcal{K}(\mathbf{q}, \dot{\mathbf{q}})$ depends on the generalized velocity $\dot{\mathbf{q}}$. From this, it directly follows that:

$$\sigma_a \coloneqq \frac{\partial}{\partial \dot{q}_1} \mathcal{K}(\mathbf{q}, \dot{\mathbf{q}}) \tag{16}$$

which is convenient since one can observe that:

$$\sigma_a = \begin{bmatrix} M_{11} & M_{12} \end{bmatrix} \dot{\mathbf{q}} = \mathbf{N}(\mathbf{q})\dot{\mathbf{q}}$$
(17)

By differentiating the last equation with respect to time, it follows that the term \ddot{q} appears in the derivative, which is proportional to the control torques, through the dynamic equation of the DIP (equation (1)). Thus, it follows that all the mechanical fluctuations at the joints are spanned over the COP by $\dot{\sigma}_a$. For supplementary details the reader can refer to (Siciliano et al., 2010; Westervelt et al., 2018). Finally, Table 3 reports the anthropometric characteristics, derived following the relations in (Winter, 2009), of the mean population used to fill the DIP/VIP model.

Table 3: Table shows the anthropometric values used to fill the $\mathrm{DIP}/\mathrm{VIP}$ model in the simulation steps.

L	l_1	l_2	m_1	m_2	I_1	I_2	K_a	K_h	B_a	B_h
(m)	(m)	(m)	(kg)	(kg)	$(kg{\cdot}m^2)$	$(kg{\cdot}m^2)$	$(N \cdot m/rad)$	$(N \cdot m/rad)$	$(N \cdot m \cdot s/rad)$	$(N \cdot m \cdot s/rad)$
0.87	0.39	0.45	19.3	40.7	2.9	7.9	366.0	246.0	22.0	22.0

315

316 Conflict of interest statement

The authors declare that there is no conflict of interest.

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Figure 1: Schematic representation of the human upright stance through a double inverted pendulum (DIP) and its induced single link inverted pendulum model (VIP). The latter virtually links the center of mass COM with the ankle joint.



Figure 2: Left panels (2a, 2c) show PSD and SDP averaged values for Y (red) and O (blue) populations. Standard deviations are represented by shaded areas. In panel 2a, vertical dashed lines indicate mean PF50 values for both groups. Vertical dashed lines in panel 2a and 2c represent respectively mean PF50 and mean T_{CR} for Y and O groups. The average regression lines obtained from DFA analysis are presented in panel 2e. Shaded areas stand for the standard deviations. In panels 2a and 2e, both axes are expressed in common logarithmic scale. Right panels (2b, 2d, 2f) show Y (red) and O (blue) groups comparisons for PF50, T_{CR} : and HE. ** indicates p<0.01 and * stands for p<0.05.



Figure 3: Panel 3a shows how PF50 varied with respect to the P and D parameters. Colormap was obtained computing PF50 from the synthetic COP time-series, obtained for each point of the P-D grid. T_{CR} and HE were computed with the same line and shown in panel 3b and 3c respectively. Shaded boxes, for Y (red) and O (blue) populations, are centered in the average P-D values (289.9 – 24.7 for Y and 360.3 - 37.1 for O), while the areas account for the standard deviation (23.4 – 20.1 for Y and 64.1 – 31.9 for O).