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# Anticipatory muscle activations to coordinate balance and movement during motor transitions: A narrative review

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## 1    1    **ABSTRACT**

## 2    2    **BACKGROUND**

3    3    Maintaining balance while moving is vital for day-to-day activities. A key challenge in the  
4    4    comprehension of human movement is to determine how muscles contribute to balance-movement  
5    5    coordination. Motor transitions, defined as movements executed between two steady balance states, are  
6    6    particularly interesting phases to study balance-movement coordination because a large, discrete change  
7    7    in whole-body momentum may disturb balance. During voluntarily-initiated motor transitions,  
8    8    anticipatory muscle patterns provide the biomechanical conditions that are favourable to both  
9    9    maintaining balance and executing the movement.

## 10   10   **RESEARCH QUESTION**

11   11   What are the mechanical consequences of anticipatory muscle activations for balance-movement  
12   12   coordination during voluntarily-initiated motor transitions?

## 13   13   **METHODS**

14   14   We review the biomechanical contributions of the anticipatory muscle activations identified in the  
15   15   literature during four types of voluntarily-initiated motor transitions, through the prism of three balance  
16   16   mechanisms ('moving the centre of pressure (CoP)', 'counter-rotating segments', and 'applying new  
17   17   external force(s)'). In particular, we investigate how anticipatory muscle activations modulate whole-  
18   18   body centre of mass acceleration.

## 19   19   **RESULTS**

20   20   We show that the mechanical consequences of anticipatory muscle activations have been extensively  
21   21   described, but mainly using the 'moving the CoP' mechanism. Unlike their role during steady balance  
22   22   states, both 'moving the CoP' and 'applying new external force(s)' mechanisms create a [required](#)  
23   23   mechanical instability during the anticipatory phase of motor transitions. The 'counter-rotating'  
24   24   mechanism may act as a stabiliser during motor transitions, but additional research is needed to clarify  
25   25   this assumption.

26 **SIGNIFICANCE**

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2 27 This review establishes that muscle activation processes have different mechanical consequences for  
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4 28 balance-movement coordination during the anticipatory phases of motor transitions, compared to steady  
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6 29 balance states. Because the mechanical instability that is created can lead to falls, a better understanding  
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8 30 of the mechanisms underlying motor transitions is needed to enable the design of more effective fall  
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10 31 prevention programs and/or devices for [population with balance deficits](#).

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16  
17 33 **KEYWORDS**

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19 34 Transition; Anticipation; Coordination; Balance; Movement  
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## 35 INTRODUCTION

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2 36 The ability to maintain balance is often take for granted. It is only when a condition impedes its control  
3  
4 37 that the vital role it plays in mobility and quality of life is appreciated. Failing to maintain balance during  
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6 38 movements leads to falls, a loss of confidence and, ultimately, loss of mobility, and decrease in quality  
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9 39 of life.

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11 40 It has long been suggested that movements disturb balance maintenance, and that appropriate muscle  
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13 41 activations are required to compensate for these disturbing forces [1,2]. According to this view, balance  
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15 42 maintenance and voluntarily-initiated movements are considered as separate processes that need to be  
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17 43 coordinated to enable efficient motor actions [3,4]. Yet, understanding balance-movement coordination  
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19 44 remains challenging.

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23 45 In this context, our narrative review of the current understanding of balance-movement coordination  
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25 46 focuses on the mechanical consequences of muscle activations during the critical anticipatory phase of  
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27 47 voluntarily-initiated motor transitions. Voluntarily-initiated movements reflect how the nervous system  
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29 48 predicts and integrates the mechanical consequences of a movement to ensure balance. When these  
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31 49 consequences cannot be accurately predicted, for example, if a person unexpectedly trips while walking  
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33 50 at a steady velocity, the predictive capacity of the nervous system is fooled. This can lead to both  
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35 51 inadequate muscle activations and segment configuration and, ultimately, result in a fall. This situation  
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37 52 illustrates the critical role of anticipation during motor transitions to ensure balance while moving.  
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42 53 This review is organised into three sections. In the first section, we introduce three key concepts of  
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44 54 balance-movement coordination: *balance*, through the three main balance mechanisms; *motor*  
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46 55 *transitions*, through a new mechanical framework; and *anticipation*, through the early muscle  
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48 56 activations related to the motor transitions performed. In the second section, we review the  
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50 57 biomechanical contributions of the anticipatory muscle activations identified in the literature during  
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52 58 motor transitions, through the prism of the three balance mechanisms. In the third section, we discuss  
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54 59 the role of these anticipatory muscle activations in balance-movement coordination, we highlight gaps  
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56 60 in the literature, and suggest new perspectives for bridging them.  
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## 61 MAIN CONCEPTS RELATIVE TO BALANCE-MOVEMENT COORDINATION

### 62 MAINTENANCE OF BALANCE AND THE THREE MECHANISMS

63 Balance has originally been related to the regulation of *posture*, *i.e.*, the ability to maintain the whole-  
 64 body in a desired segmental configuration [5]. From this perspective, balance is described by considering  
 65 the position of the whole-body centre of mass (CoM) relative to the base of support (*i.e.*, the area  
 66 surrounding all contact points with the environment) [6]. However, maintaining balance is rarely limited  
 67 to the maintenance of one posture. Mechanically, it is insufficient to only consider the position of the  
 68 whole-body CoM when it is spatially displaced, especially with a modification of the base of support. It  
 69 is also necessary to consider the linear momentum of the whole-body CoM, because its velocity enables  
 70 the determination of future whole-body CoM positions [7], which characterise the maintenance of  
 71 balance [8,9]. To generalise to all situations, we define balance mechanisms as muscle activations that  
 72 create forces that aim to accelerate or decelerate the whole-body CoM, with kinematic consequences  
 73 that correspond to the objective(s) of the task and, ultimately, prevent the whole-body from falling [6].  
 74 Human balance is usually modelled using an inverted pendulum, where the whole-body CoM oscillates  
 75 around a single point: the centre of pressure (CoP), representing the point of application of ground  
 76 reaction forces [6]. By computing the sum of external moments of a linearized inverted pendulum around  
 77 the projection of the whole-body CoM in the transverse plane on the ground ( $M'$ ) (eq. 1), Hof [10]  
 78 proposed three complementary balance mechanisms involved in motor tasks, which contribute to  
 79 modifying whole-body CoM acceleration: (1) ‘moving the CoP’, (2) ‘counter-rotating’ segment(s), and  
 80 (3) ‘applying new external forces(s)’ (Fig. 1). [The whole-body CoM acceleration can then be computed](#)  
 81 [along the antero-posterior and medio-lateral axes \(eq. 2\)](#). See Nomenclature (table 1) for definition of  
 82 all variables.

$(\overrightarrow{OP} - \overrightarrow{OM}') \times \vec{F}_G - \frac{d\vec{H}_M}{dt} + (\overrightarrow{OE} - \overrightarrow{OM}') \times \vec{F}_E = [0, l, 0]^T \times \vec{a}_M$	(eq. 1)
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$\begin{bmatrix} a_{M_x} \\ a_{M_y} \\ a_{M_z} \end{bmatrix} = \begin{bmatrix} \frac{(OP_x - OM'_x) \times F_{G_y} - \frac{dH_{M_z}}{dt} + (OE_x - OM'_x) \times F_{E_y}}{m \cdot l} \\ 0 \\ \frac{-(OP_z - OM'_z) \times F_{G_y} - \frac{dH_{M_x}}{dt} + (OE_z - OM'_z) \times F_{E_y}}{m \cdot l} \end{bmatrix}$	(eq. 2)
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84 Because  $m \cdot l$  is considered constant for a linearized inverted pendulum, only the numerators are used  
85 to describe the three balance mechanisms.

86 The ‘moving the CoP’ mechanism refers to all muscle actions that contribute to changing the CoP  
87 location within the base of support. Mechanically, changing the CoP location misaligns the whole-body  
88 weight and external force vectors, and accelerates the whole-body CoM in the opposite direction (Fig  
89 1.a) [6]. The contribution of this mechanism to whole-body CoM acceleration depends on the distance  
90 between  $P$  (the CoP) and  $M'$ , and the magnitude of ground reaction forces (eq. 3).

$\vec{a}_M = (\overline{OP} - \overline{OM}') \times \vec{F}_G$	(eq. 3)
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91  
92 The ‘counter-rotating’ mechanism refers to all muscle actions that contribute to rotating body-  
93 segment(s) that are not directly in contact with a support. When a whole-body movement is performed,  
94 it modifies the *global* whole-body angular momentum ( $H_O$ ), which is the sum of the *internal* whole-  
95 body angular momentum ( $H_M$ ) and its translational component (eq. 4):

$\vec{H}_O = \vec{H}_M + \overline{OM} \times m \cdot \vec{v}_M$	(eq. 4)
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96  $H_M$  represents the rotation of all body segments about the whole-body CoM, in a colinear reference  
97 frame, translated with respect to the global reference frame, whereas the second term illustrates the  
98 displacement of the whole-body CoM in the global reference frame,  $H_M$  can be computed using eq. 5:

$\vec{H}_M = \sum_{i=0}^n [I_i \cdot \vec{\omega}_i + (\overline{OM}_i - \overline{OM}) \times m_i (\vec{v}_{M_i} - \vec{v}_M)]$	(eq. 5)
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99 The first term in the square brackets is the angular momentum of the  $i^{\text{th}}$  segment about its centre of mass,  
 100 and the second term represents the transfer of the momentum of the  $i^{\text{th}}$  segment to the whole-body CoM.  
 101 The literature reports that  $H_M$  can also be computed about a point of the foot that approximates the CoP,  
 102 reflecting the whole-body rotation relative to the ground [11]. As long as the reference point  $M$  belongs  
 103 to the whole-body, it does not change the modulus of the internal angular momentum, but it does change  
 104 the relative contribution of each segment.

105 According to eq. 1, linear whole-body CoM acceleration is modified by the time derivative of  $H_M$ . The  
 106 counter-rotation of segments thus modifies whole-body CoM acceleration (Fig 1.b), especially when  $M'$   
 107 is outside the base of support [12].

108 The ‘applying new external force(s)’ mechanism refers to muscle actions involved in taking at least one  
 109 additional support, relative to an initial configuration, which add external force(s) that act on the whole-  
 110 body. Compared to the ‘moving the CoP’ mechanism, this mechanism modifies the area of the initial  
 111 base of support, increasing the amplitude to shift the CoP location and, therefore, to modify whole-body  
 112 CoM acceleration [10]. Well-known examples of this mechanism are *hand* placement (Fig. 1c) and *foot*  
 113 placement, which is largely used to maintain balance while walking (see [9] for a review). The  
 114 contribution of this mechanism to whole-body CoM acceleration can be quantified using eq. 6:

$\vec{a}_M = (\overrightarrow{OE} - \overrightarrow{OM}') \times \vec{F}_E$	(eq. 6)
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115 This equation is similar to eq. 3, with the difference that the distance  $\overrightarrow{OE} - \overrightarrow{OM}'$  can be larger than the  
 116 distance  $\overrightarrow{OP} - \overrightarrow{OM}'$ . It should be noted that the antero-posterior component of  $\vec{F}_G$  (eq. 3) and  $\vec{F}_E$  (eq.  
 117 6) is neglected, because the linearized inverted pendulum assumes no vertical displacement of the  
 118 whole-body CoM.

## 119 MOTOR TRANSITIONS: A NEW MECHANICAL FRAMEWORK

120 A transition is classically defined as a “change of a current state” (Cambridge Dictionary, 2024), and a  
 121 state of balance can be characterised by the whole-body CoM acceleration. Thus, in the context of human  
 122 movement, we can consider a balance state to be steady when the whole-body CoM acceleration is near

123 zero, meaning that the whole-body CoM velocity remains fairly constant (because a strictly zero whole-  
124 body CoM acceleration is impossible in humans) [13]. Classical examples of steady balance states are  
125 ‘*postures*’, where the objective is to maintain the whole-body CoM velocity close to zero, and cyclic  
126 ‘*movements*’, such as walking or running, during which there is little change in whole-body CoM  
127 velocity during a cycle, and little deviation in whole-body CoM velocity from one step to another,  
128 despite the presence of small perturbations [14].

129 Here, we define a *motor transition* as a movement phase modifying an initial steady balance state to  
130 reach another, final, steady balance state, *i.e.*, when whole-body CoM acceleration increases or  
131 decreases to change whole-body CoM velocity [15,16]. Analysis of motor transition requires the  
132 identification of the onset and end of a change in a steady balance state. We propose that a motor  
133 transition starts when the whole-body leaves an initial steady balance state (*i.e.*, when there is a  
134 noticeable increase or decrease in whole-body CoM acceleration), and ends when the whole-body  
135 reaches a final steady balance state (*i.e.*, when whole-body CoM acceleration once again approaches  
136 zero). When whole-body CoM acceleration cannot be properly computed, change in a steady balance  
137 state can also be identified by exploring the causes of the motor transition, namely through external  
138 forces acting on the whole body, or whole-body linear and angular momentum.

139 Because motor transitions are periods when whole-body CoM acceleration changes, they offer an  
140 excellent model to study balance-movement coordination. Here, we identify four mechanical types of  
141 motor transition relative to their initial and final states (*i.e.*, **required** whole-body CoM velocity) (Fig.  
142 2): *i*) posture to posture, *ii*) posture to movement, *iii*) movement to posture, and *iv*) movement to  
143 movement.

#### 144 **ANTICIPATION**

145 Humans have the remarkable ability to perform smooth movements that are temporally and spatially  
146 adapted to the objectives and constraints of the task [17]. It has been proposed that they achieve this by  
147 building internal models of the whole-body to *predict* their next whole-body state relative to the intended  
148 movement, based on the initial state and an efferent copy of the motor commands [18,19]. Because  
149 consequences of a voluntarily-initiated movement can be predicted, the nervous system can program

150 muscle activations adapted to both external and internal constraints, generating favourable  
151 biomechanical conditions for the execution of the forthcoming movement [20,21]. Such forward models  
152 appear to be essential in making motor responses coincide with predictable events, and overcoming the  
153 time delay present in the sensorimotor system when reactive control is not possible [1,22,23].

154 During voluntarily-initiated motor transitions, anticipatory muscle patterns have been defined as muscle  
155 activations or inhibitions preceding the prime mover muscle activation [4]. Although prime mover  
156 muscle activation onsets have been clearly identified when the muscle is not involved in balance  
157 maintenance, (*e.g.*, during upper-limb pointing tasks [24], a posture to posture transition), it is much  
158 more difficult to identify prime mover muscle activation onset when muscles are already actively  
159 contributing to the initial steady balance state (*e.g.*, during change of direction [25], a movement to  
160 movement transition). Thus, anticipatory activation of prime movers cannot always be used to identify  
161 the onset of voluntarily-initiated movements. Consequently, we suggest that biomechanical variables  
162 that start to change before the onset of voluntarily-initiated movements, such as changes in the pattern  
163 of external forces and/or external moments (*and therefore changes in whole-body CoM acceleration*)  
164 (subinterval (1) in Fig. 2), could be more appropriate for all types of transitions. In turn, for the purposes  
165 of this review, we define *motor anticipation* as muscle patterns that have mechanical consequences on  
166 the whole-body CoM kinematics, initiating before the onset of the *voluntary movement (e.g., raising the*  
167 *upper limb or lifting the foot to initiate gait)*. This definition enables us to consider the delay between  
168 muscle activation and muscle force production [26], without considering it as anticipation.

## 169 EVIDENCE OF ANTICIPATORY MUSCLE ACTIVATIONS MODULATING BALANCE

### 170 MECHANISMS DURING VOLUNTARILY-INITIATED MOTOR TRANSITIONS

171 In this section, we review evidence from experimental studies that recorded anticipatory muscle  
172 activations during voluntarily-initiated motor transitions. We organise this literature according to the  
173 mechanical consequences of anticipatory muscle activations, through the prism of the three balance  
174 mechanisms (Fig. 1), and focus our analysis on the anticipatory phase of the identified motor transitions  
175 (corresponding to subinterval (1) in Fig. 2). Since not all studies directly quantified the modulation of

176 each balance mechanism, in some cases we rely on findings from other studies to infer how anticipatory  
 177 muscle activations modulated the balance mechanism(s).

#### 178 **THE ‘MOVING THE COP’ MECHANISM**

179 The mechanical consequences of anticipatory muscle activations on the CoP have been largely  
 180 investigated in the sagittal plane, during motor transitions starting from a posture, such as upper-limb  
 181 pointing (posture to posture) [24], gait initiation, or squat jump (posture to movement) [27–29]. The  
 182 main anticipatory pattern of the lower-limb muscles, preceding the onset of prime mover muscle  
 183 activation is described as: activation of the tibialis anterior, coupled with inhibition of the soleus  
 184 [24,27,29,30] (Table 2). Studies also showed that the amplitude of this anticipatory pattern is modulated  
 185 by the movement velocity and/or the weight of the object to lift, the two components of whole-body  
 186 linear momentum [31–33]. The mechanical consequence of this anticipatory muscle pattern is to shift  
 187 the CoP backward. According to eq. 3, this backward CoP shift is thought to generate forward whole-  
 188 body CoM acceleration to initiate the **voluntary** movement [15,28,34–36] (Fig. 1a).

189 The mechanical consequences of anticipatory muscle activations on the CoP have also been investigated  
 190 in the frontal plane. During gait initiation (posture to movement), the anticipatory muscle pattern  
 191 responsible for the frontal displacement of the CoP has been described as a brief activation of the gluteus  
 192 medius on the swing foot side, quickly followed by decreased activation of the tibialis anterior on the  
 193 swing foot side, and the activation of the gastrocnemius medialis and gluteus medius on the stance foot  
 194 side [37,38] (Table 2). This pattern is thought to have two consecutive mechanical consequences. The  
 195 first is to shift the CoP towards the swing foot, accelerating the whole-body CoM towards the stance  
 196 foot (eq. 3). The second is to progressively shift the CoP towards the stance foot, decelerating the whole-  
 197 body CoM, enabling the swing foot unloading and lifting, while avoiding a fall towards the stance foot  
 198 side.

199 In summary, the ‘moving the CoP’ mechanism has been extensively studied during motor transitions  
 200 starting from a posture. In this case, anticipatory muscle patterns are dedicated to modifying the location  
 201 of the CoP, and changing the distance between  $M'$  and  $P$  to accelerate the whole-body CoM (eq. 3).  
 202 However, the second term, representing the ground reaction force vector in eq. 3, is generally not

203 considered, probably because it is not expected to change much during transitions with small momentum  
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2 204 (posture to posture, and posture to movement).  
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#### 5 205 **THE ‘COUNTER-ROTATING’ MECHANISM**

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7 206 During the motor transitions described in the previous section, other anticipatory muscle activations,  
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9 207 that may not contribute to CoP displacement, have been reported [39–41].  
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12 208 During bilateral shoulder flexions (posture to posture), activations of the erector spinae preceding the  
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14 209 activation of the deltoid anterior (the prime mover) have been recorded, resulting in a trunk extension  
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16 210 preceding the onset of shoulder flexion. The opposite biomechanical consequence has been reported  
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18 211 during bilateral shoulder extension, with a small trunk flexion preceding the onset of shoulder extension,  
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20 212 despite the non-systematicity of a rectus abdominis activation preceding deltoid posterior activation  
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22 213 [39]. Although the latter authors did not quantify  $H_M$ , we suggest that these rotations could illustrate a  
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24 214 ‘counter-rotating’ mechanism. Even with small angular displacements, the large inertial parameters of  
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26 215 the trunk segment should impact the whole-body CoM acceleration.  
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31 216 The following sequence of trunk muscle activations, preceding tibialis anterior activation, has also been  
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33 217 reported during gait initiation (posture to movement): activation of the bilateral rectus abdominis and  
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35 218 obliquus abdominis, accompanied by a non-systematic inhibition of the swing side erector spinae [41].  
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37 219 While these activations are likely to rotate the trunk in a forward direction, the authors did not quantify  
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39 220 trunk kinematics during this early period preceding gait initiation. During the remainder of the  
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41 221 anticipatory phase of gait initiation preceding foot off, authors have reported activations of the rectus  
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43 222 and obliquus abdominis, and the erector spinae [40,41] (Table 3).  
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47 223 Authors who have quantified trunk kinematics during the gait initiation motor transition have reported  
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49 224 results that seem to have contradictory effects on  $H_M$ . Specifically, some have shown a trunk flexion  
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51 225 preceding foot-off [40,42] (Table 3). This observation suggests that  $H_M$  should be directed in a forward  
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53 226 rotation in the sagittal plane during gait initiation. However,  $H_M$  is mostly directed in a backward rotation  
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55 227 in the sagittal plane before the foot-off during a stepping task (posture to posture transition with change  
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57 228 of base of support) [43], with the most important contribution coming from the trunk segment [44]. This  
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229 point could be clarified by identifying whether the recorded flexion of the trunk follows that of the  
1 230 pelvis, or if there is a dissociation between trunk and pelvis segments. More research is needed to  
2 231 determine whether these early trunk muscle contractions contribute to a modulation of  $H_M$  and, therefore,  
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4 232 to the control of whole-body CoM acceleration.  
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9 233 Authors reported that around the time of maximal backward CoP shift, the erector spinae of the swing  
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11 234 side are activated [40,41], and have suggested that these activations serve to limit the lateral trunk  
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13 235 inclination towards the stance foot side, and direct the trunk towards the swing foot side [40]. This lateral  
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15 236 trunk inclination should reduce the amplitude of  $H_M$  directed in a rotation towards the stance lower-limb  
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17 237 in the frontal plane. However, during a stepping task (posture to posture), some authors have reported  
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19 238 an increase in  $H_M$  directed in a rotation towards the stance lower-limb in the frontal plane [43]. As for  
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21 239 sagittal plane observations, these conclusions seem contradictory, and future studies are required to  
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23 240 precisely assess the contribution of the ‘counter-rotating’ mechanism to different types of motor  
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25 241 transitions.  
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30 242 In summary, the mechanical consequences of anticipatory muscle activations on  $H_M$  have not been  
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32 243 directly investigated during motor transitions. We are only able to infer this mechanism from  
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34 244 anticipatory muscle activations and resultant kinematics recorded during motor transitions with small  
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36 245 momentum (posture to posture, and posture to movement). Based on a limited number of studies, we  
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38 246 suggest that anticipatory trunk muscle activations could modify  $H_M$ , but direct evidence remains  
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40 247 fragmentary. Notably, it remains unknown if these anticipatory muscle activations rotate the trunk, for  
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42 248 small trunk orientation adjustments, or act to stiffen and stabilise the upper-body, particularly because  
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44 249 of the importance of stabilising the head [42,45]. Given the large inertial parameters of the trunk  
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46 250 segment, its potential contribution to whole-body CoM acceleration cannot be neglected in the  
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48 251 characterisation of balance maintenance (eq. 5). Because the contribution of the ‘counter-rotating’  
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50 252 mechanism to whole-body CoM acceleration has not been directly investigated, our conclusions remain  
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52 253 speculative. This contribution still needs to be examined across various types of motor transitions,  
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54 254 notably to clarify the role of the ‘counter-rotating’ mechanism relative to whole-body CoM acceleration  
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56 255 and, by extension, its impact on overall balance maintenance.  
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## 256 THE 'APPLYING NEW EXTERNAL FORCE(S)' MECHANISM

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2 257 The 'applying new external force(s)' mechanism relates to motor transitions starting from a movement.

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4 258 In this case, there is a modification of the base of support, for example, adapting foot placement when  
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6 259 walking on uneven terrain [46]. Because using the hand(s) for additional support rarely occurs during  
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8 260 voluntarily-initiated motor transitions, and because it is central in balance maintenance during  
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10 261 walking [9], we only selected studies that considered modification of the foot placement.

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14 262 Two distinct muscle activation mechanisms enable to modify foot placement. The first mechanism used  
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16 263 to modify foot placement is muscle activations of the swing lower-limb. These muscle activations  
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18 264 contribute to modifying the joint angles and the foot position [47]. Notably, it has been suggested that  
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20 265 the gluteus medius actively modulates medio-lateral foot placement during gait [48] (Table 4). During  
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22 266 change of direction (movement to movement), other authors reported that humans regulate the medio-  
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24 267 lateral positioning of their foot one step before changing direction, when asked to change direction early  
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26 268 in the gait cycle [49] (Table 4). Analysing a right turn, they argued that the reduction in whole-body  
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28 269 CoM acceleration in the outward direction (the left side) was explained by a reduction in the penultimate  
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30 270 step width (eq. 6) (the right foot placement). Furthermore, they suggested that this mechanical solution  
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32 271 facilitates an increase in whole-body CoM acceleration in the intended direction (the right side), in  
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34 272 addition to the lateral force this position enables.

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39 273 The second mechanism used to modify foot placement is muscle activations of the stance lower-  
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41 274 limb [47]. While walking, foot placement is closely related to the current position and velocity of the  
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43 275 whole-body CoM [9]. Authors have recorded biceps femoris activations during the penultimate step,  
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45 276 before a change of direction [25]. The same authors argued that these activations helped to limit hip  
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47 277 extension, reducing the forward velocity of the whole-body CoM and, consequently, reducing the step  
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49 278 length before changing direction. Similarly, during gait termination, activations of both soleus and vastii  
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51 279 have been recorded prior to foot contact [50,51]. Other authors have suggested that while these  
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53 280 activations may contribute to the last foot placement, they could also be related to the increase in ground  
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55 281 reaction forces measured during gait termination (eq. 6) [52].  
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282 In summary, the ‘applying new external force(s)’ mechanism makes a particularly important  
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 2 283 contribution to motor transitions that start with a movement. Foot placement can be modulated through  
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 4 284 muscle activations of both stance and swing lower-limbs, acting to modify the distance between  $M'$  and  
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 6 285  $E$  (the position of the CoP when the foot touches the ground). However, anticipatory muscle activations  
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 8 286 have been little-investigated during motor transitions, and the evolution of the ground reaction force  
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 10 287 vector has rarely been considered (eq. 6). Overall, this balance mechanism has received much less  
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 12 288 attention in the literature compared to the two others, probably because it is more difficult to identify  
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 14 289 transition onset. Thus, it seems that more research is needed to clarify which muscle activations  
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 16 290 contribute to changing foot placement during voluntarily-initiated motor transitions.  
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## 291 **DISCUSSION AND PERSPECTIVES**

292 Our objective was to provide an overview of the mechanical consequences of anticipatory muscle  
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 24 293 patterns identified during motor transitions that contribute to balance-movement coordination. *We*  
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 26 294 *proposed a new framework for motor transitions that aims to generalise the identification of the*  
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 28 295 *anticipatory period. In this framework, we classified motor transitions into four types based on their*  
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 30 296 *initial and final states. During the anticipatory period, we propose that this framework enables to identify*  
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 32 297 *the contributions of the three balance mechanisms proposed by Hof [10]—moving the CoP, counter-*  
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 34 298 *rotating, and applying new external force(s)—to the whole-body CoM acceleration. The role of each*  
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 36 299 *mechanism can thus be discussed according to the whole-body CoM acceleration required for each*  
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 38 300 *transition (Fig. 2). Consequently, this approach allows to infer on the favourable conditions anticipatory*  
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 40 301 *muscle activations provide for successful transition execution.*  
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46 302 Using this new framework, we showed that the mechanical consequences of anticipatory muscle  
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 48 303 activations have been extensively described in terms of the ‘moving the CoP’ mechanism, and mostly  
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 50 304 during motor transitions starting from postures. The mechanical consequences of anticipatory muscle  
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 52 305 activations on the other two balance mechanisms (‘counter-rotating’ segments and ‘applying new  
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 54 306 external force(s)’) have received much less attention in the literature, probably because of the difficulty  
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 56 307 of linking muscle activations to variation in  $H_M$ , and identifying activation onset of the muscle(s)  
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 58 308 contributing to changing the foot placement, respectively. Here, we discuss the potential contribution of  
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309 the identified anticipatory muscle activations to balance-movement coordination, through the prism of  
 1 changes in whole-body CoM acceleration.  
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### 5 311 **MOTOR TRANSITIONS: A PERIOD OF REQUIRED INSTABILITY**

6  
 7 312 The relative positions of the CoP and the whole-body CoM have been extensively used to characterise  
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 9 313 balance. During a *posture*, the distance between  $M'$  and  $P$  must remain small to minimise whole-body  
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 11 314 CoM acceleration (eq. 3) [6]. During a *movement*, the foot is placed such that a steady velocity can be  
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 13 315 maintained [9]. In contrast, during motor transitions, the evidence we report here suggests that  
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 15 316 anticipatory muscle activations contribute to the opposite mechanical objectives. During motor  
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 17 317 transitions starting from a *posture*, anticipatory muscle activations contribute to shifting  $P$  away from  
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 19 318  $M'$ , and during motor transitions starting with a *movement*, foot placement is shifted away from the  
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 21 319 theoretical foot position required to maintain a steady balance state. In both cases, the resulting whole-  
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 23 320 body CoM acceleration helps reaching the final state, by inducing acceleration during transitions starting  
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 25 321 from a postural state and deceleration during transitions starting from a movement (Table 2, 4). Thus,  
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 27 322 the nervous system seems to create a situation of mechanical instability (by modifying the whole-body  
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 29 323 CoM acceleration), which provide favourable conditions helping initiating or terminating whole-body  
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 31 324 movements, and transition between two steady balance states [28,31]. During motor transitions starting  
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 33 325 with a movement, such as a change of direction, this instability has been demonstrated by quantifying  
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 35 326  $H_M$ . The more medial penultimate foot placement has been related to a larger magnitude of  $H_M$ ,  
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 37 327 illustrative of mechanical instability in the frontal plane [53]. This evidence strongly suggests that the  
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 39 328 anticipatory muscle activations responsible for the ‘moving the CoP’ and the ‘applying new external  
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 41 329 force(s)’ mechanisms contribute to a short period of mechanical instability to initiate the motor  
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 43 330 transition.  
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50 331 In addition, this required mechanical instability appears to be modulated as a function of the intended  
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 52 332 motor task (*i.e.* the final state of the transition). During reaching tasks (posture to posture) in different  
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 54 333 directions, it has been suggested that anticipatory muscle activations contribute to accelerating the  
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 56 334 whole-body CoM towards the target, and do not play a role in balance maintenance during this phase  
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 58 335 [54]. During stepping (posture to posture), other authors have reported that the whole-body CoM  
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336 acceleration caused by the CoP shift is tuned to the planned foot placement, in both sagittal and frontal  
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2 337 planes [34]. These modulations support arguments that instability is required to facilitate reaching the  
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4 338 final state.

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7 339 The latter observation is aligned with recent control theory, which suggests that humans modulate their  
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9 340 initial postural state depending on the movement they expect to perform (the final state) [55]. In this  
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11 341 theory, the relative positions of  $M'$  and  $P$  are adjusted in anticipation of a motor transition, in such a  
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13 342 way that the ‘moving the CoP’ mechanism enables the motor transition to be initiated (eq. 3). However,  
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15 343 our review showed that the literature has focused on modulating the distance between  $M'$  and  $P$ , rather  
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17 344 than the magnitude of external force vectors (the ground reaction forces in eq. 3, and the new external  
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19 345 force in eq. 6). Although this vector may not change much during motor transitions with small  
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21 346 momentum (for instance during a posture to posture transition), it can have a much larger impact during  
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23 347 motor transitions with large momentum, such as a change of direction (movement to movement) while  
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25 348 running.

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30 349 When investigating upper-limb movements, some authors have suggested that it is necessary to abandon  
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32 350 the maintenance of the initial state to initiate a movement [56,57]. Our evidence of the required  
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34 351 mechanical instability reported above also supports this hypothesis in motor transitions that require  
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36 352 whole-body balance maintenance. Moreover, one study investigated voluntary sways and shoulder  
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38 353 flexion (posture to posture), and reported a decrease in muscle activations stabilising the CoP position,  
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40 354 resulting in an increase in whole-body CoM acceleration [58]. In another study, vestibular-stabilising  
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42 355 responses to electrical stimulations were reported to be proactively down-regulated before different  
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44 356 types of motor transitions [59]. In the light of our proposed mechanical framework, the abandonment of  
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46 357 the initial balance state is likely to be necessary to enable the period of required instability to transition  
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48 358 from one state to another.

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53 359 In summary, our evidence suggests that the roles of the ‘moving the CoP’ and ‘applying new external  
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55 360 force(s)’ mechanisms differ between steady balance states and motor transitions. While they help  
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57 361 maintaining balance during steady movements, these mechanisms increase mechanical instability during  
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362 the anticipatory phase of a motor transition, [creating favourable conditions helping](#) the nervous system  
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 2 363 to switch from the initial to the final steady balance state.  
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5 364 **‘COUNTER-ROTATING’, A STABILISING MECHANISM DURING MOTOR TRANSITIONS?**  
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7 365 In the previous section, we presented evidence which suggests that anticipatory muscle activations  
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 9 366 related to ‘moving the CoP’ and ‘applying new external force(s)’ mechanisms generate mechanical  
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11 367 instability [required to](#) a motor transition. This mechanical instability, which is characterised by an  
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 13 368 increase in whole-body linear and angular momenta, challenges balance and can lead to falls [60,61].  
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16 369 Since it is very unlikely that the ankle muscles alone can regulate balance [62,63], especially if the  
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 18 370 distance between  $M'$  and  $P$  is large (eq. 3), other mechanisms may limit excessive increases in whole-  
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20 371 body linear and angular momenta during motor transitions. In practice, the three balance mechanisms  
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 22 372 are not mutually exclusive, and can complement each other, depending on the objective of the task and  
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25 373 biomechanical constraints [10,64–66]. During motor transitions, the ‘counter-rotating’ mechanism may  
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 27 374 contribute to balance modulation. For instance, an anticipatory ‘counter-rotating’ mechanism has been  
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30 375 used to minimise  $H_M$  so that robots and computer animated avatar can transition without falling [67,68].  
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33 376 In human movements, however, the role of the ‘counter-rotating’ mechanism remains unclear (Table 3).  
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35 377 On the one hand, authors have reported a trunk rotation in the opposite direction from the resultant  
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 37 378 movement during shoulder flexions and extensions (posture to posture) [39]. During gait initiation  
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39 379 (posture to movement), the trunk contribution to  $H_M$  in the sagittal plane is oriented in the opposite  
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 41 380 rotational direction to that of the stance limb [44], and that of an inverted pendulum. On the other hand,  
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43 381 anticipatory trunk muscle activations and the associated trunk kinematics have been found to rotate in  
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 45 382 the direction of the [voluntary](#) movement during reaching tasks (posture to posture) [69], or in the final  
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48 383 steady state direction during the penultimate step in a change of direction task (movement to  
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 50 384 movement) [53]. In these cases, the trunk seems to contribute to increase whole-body mechanical  
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52 385 instability to initiate the motor transition. [These different contributions of the ‘counter-rotating’](#)  
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 54 386 [mechanism to balance-movement coordination could, therefore, depend on the objectives and](#)  
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57 387 [characteristics of the task \(i.e., the final state of the transition\)](#). Based on our literature review, we suggest  
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 59 388 that further research is needed to clarify the role of the ‘counter-rotating’ mechanism in balance-  
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389 movement coordination. Specifically, it is important to investigate the contribution of the ‘counter-  
390 rotating’ mechanism to the whole-body CoM acceleration, to determine whether this contribution  
391 facilitates or opposes the acceleration required for the transition.

392 One limitation of studying the ‘counter-rotating’ mechanism is that it is difficult to address the  
393 consequences of anticipatory muscle activations on  $H_M$  variation. Here, we were only able to infer the  
394 impact that anticipatory trunk muscle activations should have on  $H_M$ , based on studies that only  
395 quantified the consequences of trunk kinematics. A first step towards a better understanding of the  
396 ‘counter-rotating’ mechanism could be the quantification of each segment’s angular momentum to  
397  $H_M$  [53]. This would make it possible to differentiate between segments generating  $H_M$  that contribute  
398 to initiating the movement, and segments generating  $H_M$  that contribute to regulating balance. A second  
399 step could be to use musculoskeletal modelling to quantify the contribution of muscle activations to  
400 variation in  $H_M$  [70,71], given that the link between muscle activations and segment dynamics is not  
401 straightforward. This would make it possible to determine direct cause and effect relationships between  
402 muscle activations and  $H_M$ , notably taking internal coupling and whole-body dynamics into account.

### 403 PRACTICAL PERSPECTIVES

404 In daily life, the “forces we exert on the environment during (loco)motion are anything but  
405 constant” [72]. Given the definition of motor transitions that we propose here (*i.e.*, movement phases  
406 during which muscles produce forces that aim to change whole-body CoM acceleration), they are  
407 ubiquitous in our day-to-day movements. Changes of direction alone represent up to 50% of our walking  
408 steps [73]. These motor transitions are therefore vital for everyone to move and interact safely within  
409 their environment. For instance, most falls in older people occur following ineffective motor transition  
410 phases, *i.e.* when the whole-body CoM acceleration resulting from internal perturbation becomes  
411 excessive [74].

412 The three balance mechanisms that we identify are not mutually exclusive; instead, they are  
413 complementary processes that act together to modulate whole-body CoM acceleration [75], and their  
414 respective contributions can be analytically separated [10]. Thus, we suggest that quantifying the  
415 contribution of each of the three mechanisms to balance-movement coordination could help to improve



416 our understanding of the balance problems experienced by people with balance deficits during motor  
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2 417 transitions. For example, it has been reported that older people have a larger range of  $H_M$  in the sagittal  
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4 418 plane during stepping, compared to their younger counterparts [44]. Furthermore, after tripping, older  
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6 419 people were found to be less-able to control  $H_M$ , using their upper-limbs to prepare for impact instead  
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8 420 of reducing  $H_M$  [76], and placed their recovery limb less accurately [77], compared to their younger  
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10 421 counterparts. Therefore, older people may be less-able to adjust their whole-body CoM acceleration,  
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12 422 because of a smaller contribution of the ‘counter-rotating’ mechanism. However, these conclusions  
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14 423 remain speculative due to the limited evidence on the contribution of the ‘counter-rotating’ mechanism.  
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16 424 Another limitation is that the linearized inverted pendulum neglects the contribution of the ‘counter-  
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18 425 rotating’ mechanism in the transverse plane (eq. 2). Future studies should identify specific situations in  
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20 426 which individuals rely on ‘counter-rotating’ mechanism to regulate the whole-body CoM acceleration,  
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22 427 as well as the extent to which its use is affected by aging or various pathologies. Quantifying the role of  
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24 428 the ‘counter-rotating’ mechanism in balance-movement coordination could help determining whether  
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26 429 training to enhance this mechanism should be included in future fall-prevention and rehabilitation  
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28 430 programs.

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34 431 A better understanding of balance-movement coordination during motor transitions could also benefit  
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36 432 other populations with mobility impairments, such as amputees or exoskeleton users. Amputees lack  
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38 433 balance confidence, decreasing their mobility [78]. For example, a neural prosthesis was developed to  
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40 434 mimic the ‘moving the CoP’ mechanism of the residual lower-limb during simple posture to posture  
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42 435 transitions [79]. While this is an encouraging step towards improved mobility for amputees, the  
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44 436 prosthetic ankle was limited to only one type of motor transition with small momentum, and its control  
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46 437 is based on residual limb muscle activations. The latter point limits its potential adaptation, given the  
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48 438 asymmetric control involved in the ‘moving the CoP’ mechanism.

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52 439 For lower-limb exoskeleton users, a balance controller is required to safely perform motor  
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54 440 transitions [80]. Recently, hip exoskeletons were developed to modulate step width, and ensure balance  
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56 441 during steady walking [81]. In an able-bodied population using a lower-limb exoskeleton, trunk motion  
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58 442 and arm movements have been used to detect gait initiation [82], gait termination, and change of

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443 direction intentions [83]. Hence, combining the intention to perform a motor transition with an  
444 adaptation of the foot placement could enhance mobility in lower-limb exoskeleton users. However, to  
445 achieve this objective, further research is needed to adapt foot placement to motor transitions, while  
446 considering the abilities of different populations, notably the capacity to use the ‘counter-rotating’  
447 mechanism.

448 Finally, as a broader perspective, we propose that anticipatory muscle activations provide favourable  
449 conditions to the motor transition execution: the required mechanical instability and maintenance of  
450 balance. A better understanding of these favourable conditions may be beneficial for populations with  
451 balance deficits. Indeed, if we can better characterise these favourable conditions, then we can better  
452 understand motor transition and therefore assess more precisely which mechanisms are impaired in these  
453 populations, to provide more adapted rehabilitation programs or assistive devices.

## 454 CONCLUSION

455 The new mechanical framework we proposed for the study of motor transitions may help to better  
456 identify the underlying processes involved in balance-movement coordination. Studies have shown that  
457 anticipatory muscle activations modify whole-body CoM acceleration during the four types of motor  
458 transition. However, we demonstrated that anticipatory muscle activations have mainly been interpreted  
459 in terms of only one balance mechanism, namely ‘moving the CoP’, and during motor transitions  
460 involving small whole-body momentum (for instance during a posture to posture transition). Based on  
461 the interpretation of whole-body CoM acceleration resulting from anticipatory muscle activations, we  
462 suggest that transitions are a period of required mechanical instability that facilitates the shift from the  
463 steady balance state to a final steady balance state. This mechanical instability seems to mainly be the  
464 result of two balance mechanisms: ‘moving the CoP’ and ‘applying new external force(s)’. It appears  
465 that the ‘counter-rotating’ mechanism may be more dedicated to balance regulation, but this assumption  
466 remains to be verified, and its action may also depend on the objective and the characteristics of the  
467 task. Motor transitions are essential to ensuring mobility, and can lead to falls if they are not properly  
468 executed. We therefore suggest that improving our understanding of balance-movement coordination



1 469 during motor transitions would help in developing better rehabilitation programs and/or supporting  
2 470 devices.

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## 688 TABLES

689 Table 1: Nomenclature for equation terms (All the variables are expressed in the global reference frame)

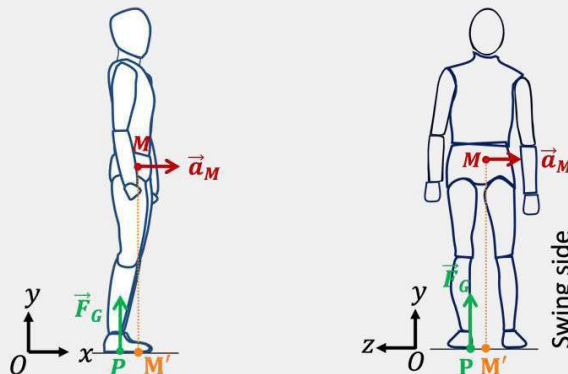
Term	Dimension	Description
$\vec{a}_M$	$3 \times 1$	Linear Acceleration of the whole-body centre of mass
$d\vec{H}_M$	$3 \times 1$	Variation of internal whole-body angular momentum
$dt$	1	Variation of time
$\vec{F}_E$	$3 \times 1$	New external force
$\vec{F}_G$	$3 \times 1$	Ground reaction force
$\vec{H}_O$	$3 \times 1$	Global whole-body angular momentum about the origin of the global reference frame
$\vec{H}_M$	$3 \times 1$	Internal whole-body angular momentum about the whole-body centre of mass
$I_i$	$3 \times 3$	Inertia tensor of the $i^{\text{th}}$ segment around its centre of mass
$l$	1	Effective pendulum length
$m$	1	Mass of the whole-body
$m_i$	1	Mass of the $i^{\text{th}}$ segment
$n$	1	Number of segments of the multi-body model
$\vec{OE}$	$3 \times 1$	Position of the application point of the new external force
$\vec{OM}$	$3 \times 1$	Position of the whole-body centre of mass
$\vec{OM}'$	$3 \times 1$	Position of the projection of the whole-body centre of mass in the transverse plane on the ground
$\vec{OP}$	$3 \times 1$	Position of the centre of pressure
$[x, y, z]^T$	$3 \times 1$	Transpose of the row vector $[x, y, z]$
$\vec{v}_{M_i}$	$3 \times 1$	Linear velocity of the centre of mass of the $i^{\text{th}}$ segment
$\vec{v}_M$	$3 \times 1$	Linear velocity of the whole-body centre of mass
$\times$		Cross product between two vectors
$\vec{\omega}_i$	$3 \times 1$	Angular velocity of the $i^{\text{th}}$ segment

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691 Table 2: Summary of the anticipatory muscle activations, biomechanical consequences, and proposed  
 692 role in balance movement coordination for the ‘moving the CoP’ mechanism during transitions starting  
 693 from a posture. The activations, biomechanical consequences and proposed role in the sagittal plane  
 694 encompass both upper-limb raising (posture to posture) and gait initiation (posture to movement) tasks,  
 695 whereas the activations described in the frontal plane are only reported during gait initiation.

‘Moving the CoP’	Transitions starting from a posture (e.g. upper-limb raising, gait initiation)	
	Sagittal Plane	Frontal Plane
Evidence of anticipatory muscle activations	Tibialis anterior activation and soleus inhibition [24,27,29,30]	Sequentially [37,38], 1) Brief swing side Gluteus Medius activation 2) Decreased swing side Tibialis Anterior activation
Biomechanical consequences of anticipatory muscle activations	Backward shift of the CoP, accelerating the whole-body CoM forward [15,34–36]	1) Shift the CoP towards the swing foot, accelerating the CoM towards the stance foot 2) Shift the CoP towards the stance foot, decelerating the CoM toward the swing foot [37,38]
Proposed role in balance-movement coordination	Required mechanical instability to help initiating the transition  Whole-body CoM acceleration required to perform the transition	Whole-body CoM acceleration required to perform the transition  Enabling the initiation of the voluntary movement and maintaining balance

#### Illustration



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697 Table 3: Summary of the anticipatory muscle activations, biomechanical consequences, and proposed  
 698 role in balance movement coordination for the ‘counter-rotating’ mechanism during transitions starting  
 699 from a posture. The activations, biomechanical consequences and proposed role in the sagittal plane  
 700 encompass both upper-limb raising (posture to posture) and gait initiation (posture to movement) tasks,  
 701 whereas the activations described in the frontal plane are only associated with gait initiation.

‘Counter-rotating’	Transitions starting from a posture (e.g. upper-limb raising, gait initiation)	
	Sagittal Plane	Frontal Plane
Evidence of anticipatory muscle activations	Bilateral activation of rectus abdominis and obliquus abdominis, with a non-systematic inhibition of swing erector spinae [40,41]	Activation of erector spinae of the swing side [40,41]
Biomechanical consequences of anticipatory muscle activations	Trunk Flexion [40,42] But $H_M$ is directed in a backward rotation [43]08/11/2024 12:42:00	Limit trunk lateral inclination towards the stance foot side [40], and direct $H_M$ in rotation towards the swing foot side [43]
Proposed role in balance-movement coordination	Unclear The dissociation between pelvis/lower-limb and trunk should be further clarified in future studies	Limit the increase in $H_M$ directed in a rotation towards the stance lower-limb side, probably to limit the increase in $H_M$ and maintain balance
Illustration		

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704 Table 4: Summary of the anticipatory muscle activations, biomechanical consequences, and proposed

705 role in balance movement coordination for the ‘applying an external force’ mechanism during transitions

706 starting from a movement. The activations, biomechanical consequences and proposed role in the

707 sagittal plane are mainly associated with gait termination (movement to posture) or to reducing whole-

708 body CoM velocity before changing direction (movement to movement), while those in the frontal plane

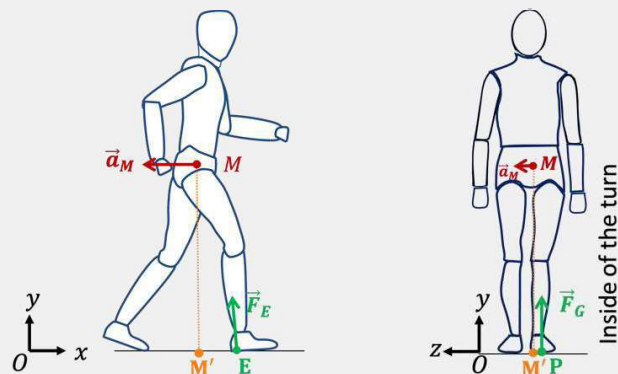
709 are mainly associated with change of direction (movement to movement).

**‘Applying an external force’**

**Transitions starting from a movement (e.g. gait termination, change of direction)**

	Sagittal Plane	Frontal Plane
Evidence of anticipatory muscle activations	1) Penultimate stance biceps femoris activation [25] 2) Swing soleus and vastii activation [50,51]	Activation of gluteus medius [48] (not directly assessed during motor transitions)
Biomechanical consequences of anticipatory muscle activations	1) Reduce gait velocity and step length [50,51] 2) Increase in GRF during the last step [52]	Reduction in the penultimate step width to reduce the CoM acceleration in the outward direction [49]
Proposed role in balance-movement coordination	Required mechanical instability to help initiating the transition  Whole-body CoM deceleration required to perform the transition	Required mechanical instability to help initiating the transition  Whole-body CoM deceleration required to perform the transition

**Illustration**



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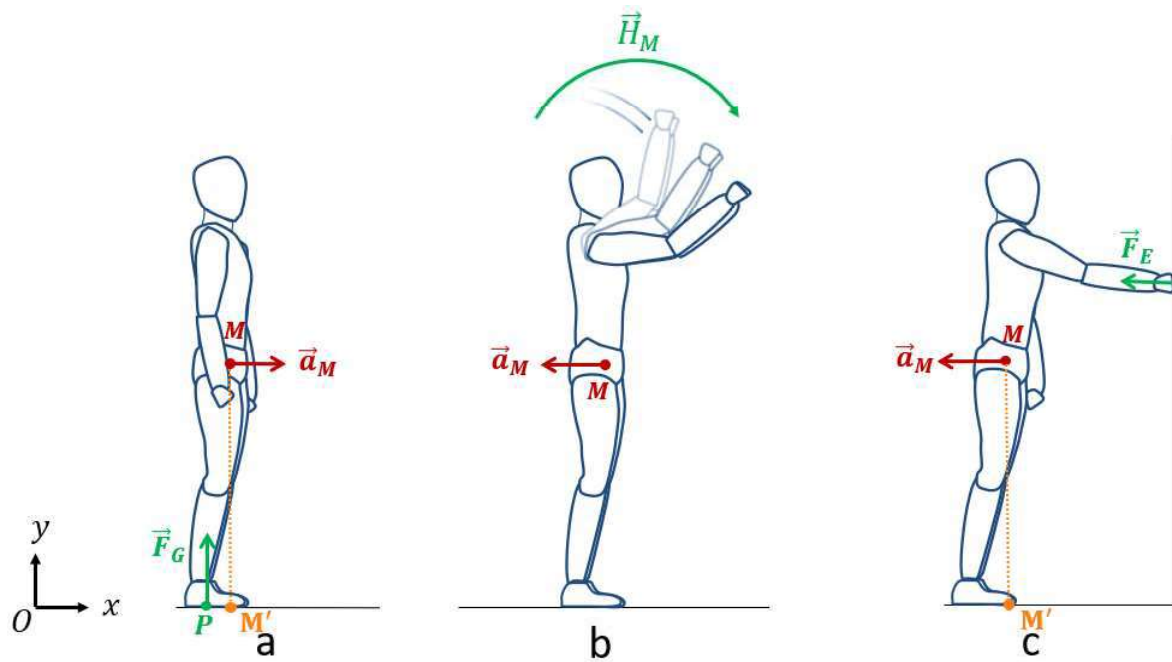
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## 711 FIGURES

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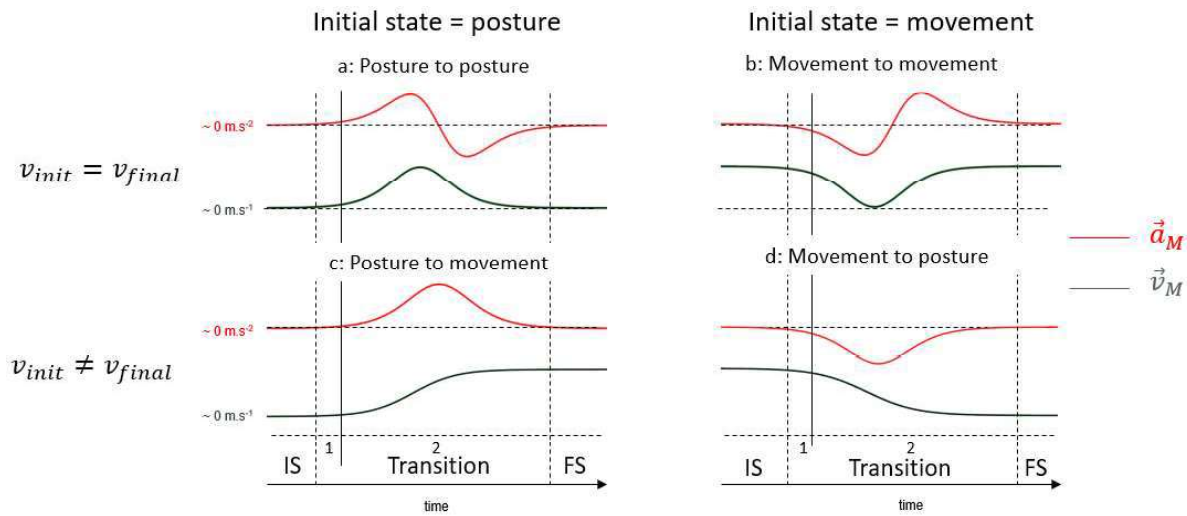


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714 Fig. 1: Schematic representation of the three balance mechanisms that contribute to modifying whole-  
 715 body CoM acceleration (red point  $M$ ) [10], here illustrated in the antero-posterior direction. a) Moving  
 716 the Centre of Pressure (green point  $P$ ) location within the base of support to modify the distance between  
 717 the centre of pressure and the projection of the whole-body COM in the transverse plane on the ground  
 718 (orange point  $M'$ ). b) Counter-rotating segments (trunk, upper limbs, etc.) modifies internal whole-body  
 719 angular momentum about the whole-body centre of mass ( $H_M$ ). c) Applying a new external force ( $F_E$ )  
 720 extends the area of the base of support, and makes it possible to modify the external forces applied to  
 721 the whole body. Green arrows indicate the primary biomechanical variables responsible for whole-body  
 722 CoM acceleration within each of the three balance mechanisms ( $F_G$ ,  $H_M$  and  $F_E$ , respectively), and red  
 723 arrows represent whole-body CoM acceleration ( $\vec{a}_M$ ).

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726 Fig 2: Schematic representation of whole-body CoM acceleration (red) and velocity (green) during the  
 727 four types of motor transitions. On the top row, transitions have identical initial and final whole-body  
 728 CoM velocities. **a:** Posture to posture: a transition between two postures, such as upper-limb pointing  
 729 or sit-to-stand tasks. **b:** Movement to movement: a transition between two cyclic movements, such as a  
 730 change of direction during walking. On the bottom row, transitions have different initial and final whole-  
 731 body CoM velocities. **c:** Posture to movement: a transition between an initial posture and a final  
 732 movement, such as gait initiation. **d:** Movement to posture: a transition between an initial movement  
 733 and a final posture, such as gait termination. Horizontal black arrow represents the interval between the  
 734 initial state (IS) and final state (FS), *i.e.*, when whole-body CoM acceleration is near zero. The  
 735 ‘Transition’ interval represents the motor transition phase. The interval (1) represents the anticipation  
 736 phase of the motor transition, *i.e.*, the change of whole-body CoM acceleration occurring before the  
 737 onset of the prime mover muscle activation (see the ‘Anticipation’ subsection) represented by the  
 738 vertical black line. The subinterval (2) represents the remaining of the motor transition.