



# Baropodometric quantification and implications of muscle coactivation in the lower limbs caused by head movement: A prospective study

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Title:

Baropodometric quantification and implications of muscle coactivation in the lower limbs caused by head movement: a prospective study

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- 1 Baropodometric quantification and implications of muscle coactivation in the
- 2 lower limbs caused by head movement: a prospective study
- 3
- 4

5 Background: In healthy young adults, muscle coactivation can sometimes be  
6 induced by remote voluntary contractions when the motor task is forceful,  
7 maximal, tiring, or cyclic and brief.

8 Objectives: To show that a change in plantar pressure is an unequivocal  
9 response to backward movement of the head, and to contribute to a better  
10 understanding of physiotherapy methods that involve remote muscle  
11 activation.

12 Methods: Involuntary coactivation was quantified as a percentage of the  
13 anteroposterior plantar pressure distribution, using a baropodometric  
14 platform in a population of young adults. The baropodometric data were  
15 collected from a 1-second recording after 30 seconds in the reference  
16 condition, and from 1-second recordings during the first second and then  
17 during the 120th second in the test condition. The results were analyzed with  
18 Bayesian statistics (Markov chains and Monte Carlo integration techniques).

19 Results: 90 adults participated in the study (age range: 19-26; 38 males and  
20 52 females). The forefoot plantar pressure increased in all cases, by a mean  
21 multiplicative factor (on a logit scale) of 1.12 (from 72.24% to 74.45%) when  
22 the head was aligned over the trunk.

23 Conclusions: This 90-participant trial confirmed our initial hypothesis: a  
24 increase in forefoot plantar pressure is a systematic response to the motor  
25 task (head movement), and suggests greater recruitment of the plantar flexor  
26 muscles. A spinal reflex and/or a previously unknown form of motor overflow  
27 might be involved in this phenomenon. These results support the  
28 development of inductive physiotherapy techniques based on remote muscle  
29 activation in the treatment of musculoskeletal disorders.

30     ClinicalsTrial.gov identifier: NCT02320097

31

32

33    Keywords:

34    motor irradiation; baropodometry; plantar pressure; inductive physiotherapy

35

## 1. INTRODUCTION

Ever since Sherrington's seminal work on spinal reflexes, it has been known that the execution of a coordinated motor task requires the concurrent activation of several muscle groups by the central nervous system (CNS) ([Gelfand et al 1971](#)). Bernstein showed that this grouping strategy simplifies the task's control by the CNS ([Bernstein 1967](#)). These functional synergies between muscles - initiating the movement, counteracting it, and stabilizing the position of the mobilized joints ([Bouisset et al 1977](#)) - also apply to postural muscles involved in the maintenance of balance in upright stance ([Yang et al 2015](#)).

However, not all physiological coactivations show synergistic patterns. Some types of coactivation (mainly those due to spinal reflex facilitation) are induced at the same time as a remotely performed motor task ([Zehr & Stein 1999](#)). For example, clenching the jaw and hooking the flexed fingers together while attempting to pull the hands apart (as in the Jendrassik maneuver) is an upper-body task that might facilitate the concurrent activation of lower-body muscles (e.g. the soleus) ([Dowman & Wolpaw 1988](#)). This unintentional coactivation of the soleus can be evidenced by sudden increases in the H-reflex amplitude and in voluntary baseline EMG activity ([Ertuglu et al 2018](#)). When this activation persists over time, it is possible to measure an increase in the force generated by the coactivated muscles by using the concurrent activation potentiation phenomenon ([Ebben 2006](#)).

Other involuntary coactivations induced in non-homologous muscles that are ipsilateral or contralateral to the motor task (as in associated movements) ([Abercombie et al 1964](#)) or in contralateral homologous muscles (as in mirror



61 movements) ([Armatas et al 1994](#)) have been ascribed to a motor overflow  
62 phenomenon ([Hoy et al 2004a](#)).

63 These coactivations have also been interpreted as a failure to inhibit  
64 involuntary muscle activity in the passive limb ([Mayston et al 1999](#)); they  
65 appear frequently in children under the age of 10 and in neurologically  
66 healthy elderly individuals ([Hoy et al 2004a](#)). In the young adult, muscle  
67 coactivation mostly occurs when the motor task recruits the distal muscles of  
68 the upper extremities (e.g. finger-pressing tasks) ([Ada & O'Dwyer 2001](#)), is  
69 complex, requires maximal force, or produces substantial fatigue ([Hoy et al](#)  
70 [2004a](#)).

71 In routine clinical practice, our observations of the standing position  
72 evidenced a recurrent involuntary foot response that appears concurrently  
73 with a remote voluntary backward movement of the head.

74 In clinical terms, this response translates into a plantar pressure increase  
75 under the forefoot. This is why we used a baropodometric platform to  
76 quantify the anteroposterior pressure distribution (as the percentage  
77 increase) in a population of young adults.

78 The influence of the measurement time-point, the magnitude of the head  
79 displacement in the experimental condition, and the participant's handedness  
80 on the anteroposterior pressure distribution were also assessed. The  
81 pressure increase was suggestive of involuntary muscle contractions, given  
82 that experimental template used with all the participants reduced the level of  
83 noise associated with the need to maintain balance in the standing position.  
84 Hence, the involuntary lower-body muscle activation induced by remote,  
85 voluntary activation of upper-body spinae was indirectly quantified in a novel

86 way by applying a tool generally used to analyze foot problems (pain,  
87 postural disorders, deformities, etc.) ([Rosario 2014](#)).

88 The objectives of the present 90-participant trial were to demonstrate that an  
89 increase in forefoot plantar pressure is a systematic response to backward  
90 movement of the head and to contribute to a better understanding of  
91 physiotherapy methods that involve remote muscle activation; this may have  
92 direct clinical relevance in novel therapeutic strategies (e.g. normo-inductive  
93 physiotherapy) based on the use of remote motor irradiation to treat patients  
94 suffering from musculoskeletal disorders. This type of therapeutic strategy  
95 can be particularly relevant when direct solicitation techniques are ineffective  
96 or inapplicable.

97

## 98 **2. METHODS**

### 99 **2.1. Participants**

100 This was a prospective, open-label, single-center, single-group study in  
101 the Clinical Investigation Centre (INSERM CIC 1434) at Strasbourg  
102 University Hospital (Strasbourg, France). All the participants were  
103 physiotherapy students recruited from the *Institut de Formation en Masso-*  
104 *Kinésithérapie* (Strasbourg, France). The study was approved by the local  
105 investigational review board (*CPP Est IV*, Strasbourg, France; reference:  
106 14/46), and was performed in accordance with the tenets of the Declaration  
107 of Helsinki (1964) and its updates. All participants gave their prior, written,  
108 informed consent. None of the participants reported neuromuscular,  
109 orthopedic or musculoskeletal disorders, or known pregnancy ([Table 1](#)).

110 Bodyweight, height, shoe size, and handedness were documented for each  
111 participant.

112 TABLE 1

## 113 2.2. Procedure

114 To quantify the anteroposterior distribution of the static plantar pressures,  
115 following a Win-Pod baropodometry platform was used ([Etter et al \(2015\)](#)):  
116 sensing area, 400 mm x 400 mm; sampling rate, 200 images per second;  
117 pressure range per sensor, 0.4 to 100 N; 2304 sensors; Win-POD software  
118 (version 6, Medicauteurs SA, Toulouse, France). An algorithm divided the  
119 foot's total surface area into equal anterior and posterior zones. The  
120 baropodometric recordings were homogenized by centering the plantar  
121 pressures graphs within the same spatial reference frame.

122 To standardize the experimental conditions and thus reduce possible bias  
123 related to differences in the participants' standing position, we used a single  
124 template for all participants. This comprised a horizontal surface (the force  
125 platform) and a vertical surface (a backboard located directly behind the  
126 participant's body). The anterior and plantar pressures was recorded (as a  
127 percentage of the total pressure) under in two postural conditions ([Figs. 1,2](#)):

128 - Reference condition: the heels, buttocks and scapular area were in  
129 contact with the backboard, and the head was in a natural position (i.e. not  
130 requiring voluntary contractions). The natural head-board distance varied  
131 from one participant to another but was always recorded (in mm).

132 - Test condition: the head was no longer in its natural position but was in  
133 contact with the backboard. To align the head in the same sagittal plane as  
134 the other body masses, the participant had to move it backwards without

135 changing the head's angle with regard to the horizontal place. The participant  
136 had to maintain the aligned head position for 120 s, requiring sustained  
137 isometric and symmetric contractions of upper-body spinae muscles.  
138 The following time points selected for statistical analysis: a 1-second  
139 recording after 30 seconds in the reference condition (providing a "snapshot"  
140 of the plantar pressures); a 1-second recording during the first second and a  
141 1-second recording of 120th second in the test condition (in order to compare  
142 two time points, rather than a mean measurement over the entire 120 s  
143 period).

144 FIGURES 1AND 2

145

### 146 2.3. Sample size

147 On the basis of a pilot study of a participant whose forefoot plantar  
148 pressure increased by 5% following alignment of the head with the  
149 backboard, we calculated that a total sample size of 90 participants would  
150 yield a power of about 95%. Hence, 10000 data files were simulated using a  
151 mean value of 5% for the percentage increase in forefoot plantar pressure  
152 and a standard deviation of 2.5% - a rather high but nevertheless acceptable  
153 level of variability.

154

### 155 2.4. Statistical analysis

156 The forefoot plantar pressure distribution was expressed as a percentage  
157 (from 0% to 100%); hence, a non-bounded distribution (such as a normal  
158 distribution) could not be assumed. Accordingly, we transformed the data into  
159 a beta distribution by dividing the percentage by 100 (yielding values of

160 between 0 and 1, corresponding to the support of a beta distribution). We  
 161 used a Bayesian statistical approach based on Markov chains and Monte  
 162 Carlo integration techniques (using OpenBUGS software) (Lunn et al 2000).  
 163 After 5,000 burn-in iterations, the application of three chains with 50,000  
 164 iterations and a thinning factor of 10 yielded a total of 15,000 iteration  
 165 samples for *a posteriori* estimates. The model with respect to the study's  
 166 main objective was a mixed beta regression model with covariates that  
 167 explained the mean of the beta distribution. More specifically,  $y_i$  (the  
 168 percentage plantar pressure under the forefoot, transformed into a (0-1)  
 169 range) for participant  $i$  in a given motor task was assumed to be beta-  
 170 distributed with the parameters  $\alpha_i$  and  $\beta_i$ . Given that these parameters are  
 171 not directly understandable, the distribution was reparametrized using the  
 172 mean  $\mu$  and the precision  $\phi$ , where  $\mu_i = \frac{\alpha_i}{\alpha_i + \beta_i}$  and  $\phi = \alpha_i + \beta_i$ . A vague  
 173 gamma prior (with the parameters 0.001 and 0.01) was assigned for the  
 174 common precision. Next, the  $\mu$  values were additively structured with a logit  
 175 link. The linear predictor for the subject  $i$  was:

$$\text{logit}(\mu_i) = a_0 + a_1 I(C_i = 1) + a_2 M_i + a_3 D_i + a_4 L_i + b_i$$

176 where:

- 177 •  $I(C)$  stands for the dummy function, whose value is 1 when condition  $C$  is  
 178 fulfilled and 0 when it is not fulfilled;
- 179 • the different conditions were recoded into two modalities: the first for the  
 180 head held in a natural, neutral position (the reference condition, where  
 181  $C=0$ ) and the second for the head aligned with the backboard (the test  
 182 condition, where  $C=1$ ). A dummy variable was added to take account of an  
 183 additional condition:  $M$  for maintenance of the backwards head position;

- 184 •  $D$  is the head-backboard distance in the neutral position;
- 185 •  $L$  is an indicator of the participant's handedness (0: left-handed; 1: right-
- 186 handed).
- 187 •  $b_i$  is a random participant effect, modelled with a precise, zero-mean
- 188 normal prior.

189

190 With regard to interpretation of the parameters and the logit scale, the  $a$   
191 *posteriori* distribution of  $\frac{\exp(a_0)}{1+\exp(a_0)}$  (referred to as the expit function) provides  
192 an estimate of the forefoot pressure distribution for a left-handed participant  
193 in the neutral condition. Next, the  $a$  *posteriori* distribution of  $\exp(a)$ s provides  
194 an estimate of the mean increase in forefoot pressure:  $\exp(a_1)$  for alignment  
195 of the head with the board,  $\exp(a_2)$  for measurement after 120 seconds (if  
196 the head is not in the spontaneously chosen position),  $\exp(a_3)$  when the  
197 distance to the backboard increases by 1 cm, and  $\exp(a_4)$  if the participant is  
198 right-handed.

199 Lastly,  $\frac{\exp(a_0+\dots)}{1+\exp(a_0+\dots)}$  provides an estimate of the resulting forefoot plantar  
200 pressure distribution; for example,  $\frac{\exp(a_0+a_1)}{1+\exp(a_0+a_1)}$  is the mean forefoot plantar  
201 pressure distribution when the head moves back to the backboard.

202 Given the complexity of this model, we first determined whether the  
203 participant's handedness, the distance from the backboard, and the  
204 maintenance of a position for 120 seconds were statistically significant by  
205 inspecting the parameter's  $a$  *posteriori* distribution. If 0 was included in the  
206 95% credible interval, the parameter was considered to be non-significant  
207 and removed from the model. Once these three parameters had been

208 assessed, the final model was built and the *a posteriori* distributions were  
209 estimated.

210

### 211 **3. RESULTS**

212 90 individuals volunteered to participate in the study (out of a target  
213 population of 134): this number corresponded to the required sample size. 2  
214 volunteers could not be included, and so 2 other volunteer participants were  
215 selected at random from the target population. The characteristics of the  
216 study population are summarized in [Table 2](#).

#### 217 **TABLE 2**

218 Datasets for 90 participants were analyzed. With a confidence interval of  
219 95%, neither the measurement time point (0.0192 [-0.065; 0.103]), the head-  
220 backboard distance (0.0342 [-0.092; 0.182]), nor the participant's  
221 handedness (-0.032 [-0.409; 0.421]) were significant. Accordingly, these  
222 variables were removed from the model. [Table 3](#) summarizes the forefoot  
223 pressure (as a percentage) under the various conditions.

224 The *a posteriori* plantar parameters of interest (derived from the reduced  
225 model) are summarized in [Table 4](#). In the reference condition, the mean  
226 forefoot plantar pressure [95% confidence interval] was 72.44% [69.94-  
227 74.79]; the alignment of the head over the trunk increased the forefoot  
228 plantar pressure by a multiplicative factor (on a logit scale) of 1.12 [1.05-  
229 1.20], yielding a mean value of 74.67% [72.38-76.8].

#### 230 **TABLES 3 AND 4**

### 231 **4. DISCUSSION**

232 In our population sample, the statistically significant increase in forefoot  
233 plantar pressure (relative to the reference condition) following the backward  
234 alignment of the head over the other body masses was solely dependent on  
235 the test condition. The measurement time point (120 seconds), the  
236 magnitude of the head displacement (the head-backboard distance) and the  
237 participant's handedness (right-handedness for 91% of the participants,  
238 much as in the general population ([Coren 1993](#))) did not modulate the  
239 pressure distribution. This result agrees with and extends those of our earlier  
240 study of 50 healthy young adults (with an identical design: the Win-Pod  
241 baropodometry platform and the standardized template); the test condition  
242 featured the alignment of the pelvic and thoracic masses with the backboard  
243 ([Nisand et al 2016](#)).

244 The hypothesis of a mechanical phenomenon based on a purely gravity-  
245 based model can be immediately ruled out. Indeed, according to this model,  
246 the resultant of shifts in the center of pressure should act first forwards (due  
247 to anticipatory postural adjustments that precede balance perturbations  
248 associated with the head movement) and then rearwards (due to the  
249 backward movement of the head's mass, which accounts for about 8% of the  
250 bodyweight, without any other body masses moving). Hence, for a purely  
251 mechanical phenomenon, the increase in plantar pressure should have  
252 occurred under the hindfoot ([Vandervael 1966](#); [Massion 1992](#); [Bouisset & Do](#)  
253 [2008](#)).

254 An increase in the percentage of forefoot plantar pressure is necessarily  
255 an expression of increased plantar flexor muscle activity. This does not rule  
256 out (i) a possible coactivation of the dorsal flexor muscles (ii) naturally more



257 powerful plantar flexor muscles; or (iii) naturally less powerful but more  
258 intensely activated dorsal flexor muscles. This is why we recorded the  
259 surface EMG activity of the gastrocnemius medialis, soleus and tibialis  
260 anterior muscles in 6 participants; this evaluation was not initially planned in  
261 the study protocol. These recordings confirmed the systematic activation of  
262 gastrocnemius medialis and soleus, as well as the almost total absence of  
263 anterior tibialis activity. Even though these data cannot evidently be  
264 generalized to our whole study population, they argue in favor of a single  
265 involuntary motor response: contraction of the plantar flexors. The  
266 experimental template (consisting of the force platform and the backboard)  
267 removes or at least reduces the noise associated with the need to maintain  
268 balance in the standing position. However, one cannot rule out a potential  
269 modulation of the motor response by the template. Additional studies in the  
270 absence of a template could explore this hypothesis.

271 If the mechanical hypothesis is abandoned in favor of a neuromuscular  
272 hypothesis, one must consider whether the increase in plantar flexor activity  
273 is due to physiological postural instability caused by the change in head  
274 position. It is well known that the vestibular, proprioceptive and visual  
275 systems are sensitive to the head position and are involved in postural  
276 stability. The cerebellum (which is directly related to these systems) and the  
277 spinal cord are also involved, however, these were not assessed within the  
278 present study ([Nashner & Wolfson 1974](#), [Nashner & McCollum 1985](#),  
279 [Deliagina & Orlovsky 2002](#), [Horak & McPherson 1996](#) ). Several hypotheses  
280 could be therefore considered with regard to this increase: (i) a vestibular  
281 sensory disturbance that occurs when the utricle (an otolith organ) is outside

its working range (Brandt et al 1981); (ii) an impairment in cervical proprioceptive information that increases the ankle torque and the activity of the soleus muscle (Vuillerme & Rougier 2005), and (iii) a lack of vision, which disrupts the visual inputs in postural control and increases the level of muscle activity at the ankle (Rougier 2003). Similarly, one should also consider a change in postural mechanics due to a displacement of the center of mass away from the ankle joint, changing the ankle moment and thus increasing the muscle activity in lower limbs (Buckley et al 2005). One can also consider postural synergies in which ankle muscles (the soleus, medial gastrocnemius, or anterior tibialis) are coactivated to maintain balance (Yang et al 2015). However, these hypotheses can reasonably be ruled out in our study, for the following reasons: (i) the head moved rearwards, without increasing the degree of lordosis; (ii) the variations in the ankles' flexion-extension angle and thus the noise associated with maintaining balance were neutralized by the use of a standardized template; (iii) the anteroposterior plantar pressure distribution was recorded for 120 s during maintenance of the test condition, i.e. after the disturbance related to the head movement; (iv) even when possible vestibular interference is taken into account, it is likely that maintenance of the position for 120 s will have neutralized this influence; and (v) the reference and test conditions were performed with eyes open.

Hence, the facilitation of spinal reflex responses appears to be credible and must be considered in more detail. It has been suggested that hyperexcitability in the spinal cord's alpha motoneuron pool and a subsequent increase in the H reflex amplitude explain involuntary coactivations via activation of the muscle fibers innervated by these neurons

307 ([Schieppati 1987](#)). For example, this type of reflex phenomenon was  
308 evidenced (i) in the soleus muscle by remote voluntary contractions of the  
309 muscles of the jaws, forearms and hands (the Jendrassik maneuver), and (ii)  
310 in the flexor carpi radialis muscles by remote voluntary contractions of the  
311 contralateral ankle flexor muscles ([Zehr & Stein 1999](#); [Ertuglu et al 2018](#)).

312 An irradiation process via motor overflow is another plausible, coherent  
313 hypothesis - even though the characteristics of our present task contrast with  
314 those described in the literature ([Ada & O'Dwyer 2001](#); [Honaga et al 2007](#)).  
315 Irradiation by motor overflow is defined as a voluntary movement (the  
316 backwards alignment of the head, in our case) that triggers an involuntary  
317 motor response of remote muscles (the plantar flexor muscles, in our case)  
318 ([Hoy et al 2004a](#)). Indeed, the simple voluntary task studied here  
319 (displacement of the head using the template) required very little force and  
320 was not tiring. In contrast, this head movement counteracts the participant's  
321 forward postural habitus of the head - the most common misalignment  
322 relative to an ideal head posture in the sagittal plane. This characteristic  
323 seems decisive for triggering an irradiation process, although it would be  
324 interesting to establish whether other movements have this particular feature.  
325 Most of our study participants were not conscious of the involuntary  
326 coactivation. When the participant was conscious of the coactivation, they  
327 were unable to inhibit it by voluntary, higher-order cognitive control (i.e.  
328 directed attention); this contrasts with the motor overflows described in the  
329 literature ([Addamo et al 2010](#)). This particularity suggests that the muscle  
330 coactivation observed in our study is of subcortical origin but does not rule  
331 the involvement of functional cortical connections (related to the cortical

332 connection theory, the transcallosal facilitation hypothesis, and/or the  
333 transcallosal inhibition theory) ([Hoy et al 2004a](#); [Ebben 2006](#); [Addamo et al](#)  
334 [2007](#)).

335 In patients with plantar flexor disorders, targeting these muscles by remote  
336 activation may be a relevant therapeutic strategy whenever direct solicitation  
337 techniques are ineffective or inapplicable (e.g. due to the presence of acute  
338 pain, bone and joint trauma, or peripheral paralysis in the affected area). A  
339 remote muscle activation strategy can be used to strengthen the target  
340 muscles, increase their endurance, enhance joint flexibility or improve  
341 postural stability ([Ebben 2006](#), [Vicky et al 1993](#)). A remote muscle activation  
342 strategy can also be used for normalizing excessive residual muscle tension  
343 and thus relieving harmful mechanical stress on bone and joint structures.  
344 The latter option is the basis of normo-inductive physiotherapy techniques:  
345 the inductive movement (the voluntary motor task) is carried out continuously  
346 until the remote involuntary motor response is extinguished. Certain clinical  
347 outcomes (such as reduced pain levels and improvements in dysfunction and  
348 acquired deformities of the musculoskeletal system) seem to be correlated  
349 with this extinction. The observed extinction of the remote involuntary motor  
350 response suggest the induced “normalizing” muscle activity has a positive  
351 effect ([Destieux et al 2013](#); [Nisand et al 2015](#); [Nisand et al 2016](#); [Callens et](#)  
352 [al 2017](#)).

## LIMITATIONS

The present study had several limitations. Firstly, the baropodometry data could not tell us (i) which plantar flexors were activated, (ii) whether one

plantar flexor was activated more than the others, or (iii) whether or not dorsal flexors were coactivated. These questions could have been addressed by using EMG to identify and characterize activations and coactivations. Nevertheless, the baropodometry platform enables us to quantify induced muscle activity.

Secondly, the age range of the study population (healthy young adults aged 19 to 26) was quite narrow; hence, our results cannot be extrapolated to older adults.

## **5. CONCLUSION**

The results of this 90-participant trial tended to confirm our initial hypothesis: the involuntary, systematic coactivations that appeared simultaneously in both lower limbs (as evidenced by an increase in forefoot plantar pressure) were triggered by remote voluntary muscle contractions – a motor task that was neither complex, demanding, tiring, cyclic nor brief. This finding is suggestive of a spinal reflex or (more plausibly) a previously unknown form of motor overflow. Further research will be needed to (i) define the electrical characteristics of this coactivation (using EMG recordings), (ii) investigate the neural networks involved in this phenomenon (using imaging or transcranial magnetic stimulation), and (iii) determine the therapeutic effects of the remote voluntary contractions triggered by applying normo-inductive physiotherapy techniques.

## Clinical Relevance

- In patients with plantar flexor disorders, targeting the latter muscles via remote activation might be a relevant therapeutic strategy whenever direct solicitation techniques are ineffective or inapplicable.
- Typically, indirect solicitation techniques are intended to strengthen the target muscles, increase their endurance, enhance joint flexibility, and improve postural stability.
- In normo-inductive physiotherapy, indirect solicitation techniques seek to normalize excessive residual tension in the target muscles and thus relieve the associated symptoms.

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#### Declaration of interest

The authors declare that they have no competing interests.

#### Authors' contributions

MN, CC, CM and ES designed and led the study; J-BC, CC and CD collected the data. ES analyzed the data, and all authors interpreted the data. MN, CC and CD drafted the manuscript, and all co-authors revised it critically for important intellectual content. All authors have read and approved the final manuscript.

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## Figure legends:

Figure 1: The experimental conditions.

- a) The template comprised a horizontal surface (materialized by the force platform) and a vertical surface (materialized by a backboard located directly behind the body).
- b) The participant stands on the baropodometric platform with his/her arms by the side of the trunk, barefoot, and wearing close-fitting underwear and a shower cap. He/she looks straight ahead, with a horizontal gaze and the eyes open. The heels (with the feet together), buttocks and scapular area are in contact with the backboard. No specific instructions are given concerning the position of the head: it is held in a spontaneously chosen, natural position that does not require any muscle contraction.
- c) In the reference condition, the head is held at a certain, spontaneously chosen distance from the backboard. This distance was measured in mm. A vertical slot in the board increased the accuracy of this measurement.
- d) After a voluntary backward movement of the head (so that the head was in contact with the backboard), the participant maintained this position for 120 seconds.



Figure 2: An example of the pressure distribution on the force platform.

For this participant, in the reference condition, the forefoot pressure (measured as a percentage of the total) is 43% for the left forefoot and 42% for the right forefoot. In the test condition, these values were respectively 81% and 73%.



## C0: The reference condition

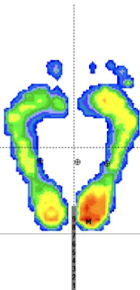
065	Age : 20 ans	Pathologie :
H	Poids : 54 Kg	
	Taille : 166 cm	
Correspondant :	Pointure : 39,	
	Date : 11/02/2015	

### Analyse statique

T0 libre  
Dorsaire

Surface : 44 cm<sup>2</sup>  
Poussée : 19 %  
Répartition : 43 %

Surface : 46 cm<sup>2</sup>  
Poussée : 24 %  
Répartition : 42 %



Surface : 40 cm<sup>2</sup>  
Poussée : 25 %  
Répartition : 57 %

Surface : 40 cm<sup>2</sup>  
Poussée : 33 %  
Répartition : 58 %

## C1: The test condition

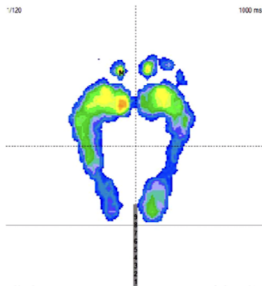
065	Age : 20 ans	Pathologie :
H	Poids : 54 Kg	
	Taille : 166 cm	
Correspondant :	Pointure : 39,	
	Date : 11/02/2015	

### Analyse posturologique

Tête mur

Surface : 54 cm<sup>2</sup>  
Poussée : 44 %  
Répartition : 81 %

Surface : 56 cm<sup>2</sup>  
Poussée : 33 %  
Répartition : 73 %



Surface : 28 cm<sup>2</sup>  
Poussée : 10 %  
Répartition : 19 %

Surface : 31 cm<sup>2</sup>  
Poussée : 12 %  
Répartition : 27 %

Table 1: Eligibility criteria applied to the study population

Inclusion criteria	<ul style="list-style-type: none"> <li>• Age between 18 and 30</li> <li>• Social security coverage</li> <li>• Ability to understand the study's objectives, procedures and risks, and to provide written, informed consent</li> </ul>
Exclusion criteria	<ul style="list-style-type: none"> <li>• Past or concomitant infectious or cancerous diseases of the spine</li> <li>• Vertebral osteosynthesis</li> <li>• Acute neck or arm pain</li> <li>• Limb trauma in the previous 12 months</li> <li>• Acute leg pain</li> <li>• Neuropathic disease or the sequelae of neuropathic disease of the legs</li> <li>• Myasthenia gravis</li> <li>• Central nervous system disorders</li> <li>• Inner ear problems</li> <li>• Subjects under legal guardianship</li> <li>• Known pregnancy</li> <li>• Simultaneous participation in another biomedical research study of a drug or medical device</li> </ul>

Table 2: Characteristics of the study population (90 healthy young adults)

Gender	Males: 38	Females: 52
Handedness	Left-handed: 8	Right-handed: 82
Age	20.6 ± 1.3 (19-26)	
Bodyweight	65.7 ± 11.0 kg (44.6-113.5)	
Height	171.2 ± 8.8 cm (152-201)	
Shoe size	40.6 ± 2.8 (36-48)	
Head-backboard distance (in C0)	36.3 ± 17.4 mm (0-84)	

Quantitative variables are quoted as the mean ± standard deviation (range).

Table 3: Summary of forefoot plantar pressure (as a percentage) under the experimental conditions

	Reference condition	Test condition	
		0 s	120 s
Mean (SD)	71.2 (11.0)	73.8 (10.8)	72.9 (11.3)
Quartile 1	63.7	66.0	65.0
Quartile 2	71.0	74.0	72.0
Quartile 3	79.0	82.0	81.0

SD: standard deviation

Table 4: The parameters' *a posteriori* distributions in the reduced model

	mean (SD)	median	95% confidence interval
Forefoot plantar pressure			
reference condition (%)	72.44 (1.229)	72.50	[69.94; 74.79]
test condition (%)	74.67 (1.111)	74.68	[72.38; 76.80]
Multiplicative factor	1.122 (0.0382)	1.122	[1.049; 1.2]
Model parameters			
Intercept	0.9672 (0.06157)	0.9692	[0.8443; 1.087]
Backward head effect	0.1148 (0.03403)	0.1153	[0.04786; 0.1822]

SD: standard deviation