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Do bimanual isometric push efforts in humans stop as a consequence of postural muscle exhaustion?

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Abstract

The purpose of this study was to explore whether global efforts stop as a consequence of postural muscle exhaustion. To this end, seated adults were asked to exert 75% maximal voluntary contractions bimanual push efforts until exhaustion. A dynamometer was used to measure the horizontal force exerted on a bar (Fx) and a custom-designed force plate measured the antero-posterior displacement of the centre of pressure (Xp). Electromyograms were picked up by bipolar surface electrodes from the primum movens (serratus anterior) and four postural muscles (trapezius superior, erectores spinae, rectus abdominis, rectus femoris). Root mean square and mean power frequency were calculated over 2-s intervals and compared to corresponding Fx and Xp values. It was shown that the effort stops as a consequence of exhaustion of postural muscles (rectus abdominis and rectus femoris), and not of the primum movens. It is concluded that postural muscles make a major contribution to global efforts, in that they allow compliance to biomechanical requirements, that is, to preserve the distance between the centre of pressure and the centre of gravity, which must be proportional to the external force.

Keywords: Global effort; Isometric force; Fatigue; Postural muscles; Electromyography

Most motor acts require the contribution of numerous joints, which compose multi-joint articulated chains and are controlled by complex muscular patterns. The external efforts they exert are qualified as 'global' (or 'synthetic'). When the extremities of the chain are constrained and cannot be moved, the chain is considered closed. For example, when pushing on a bar, the articulated chain, located between the bar, where the external force is exerted, the seat and the ground, is closed. However, many degrees of freedom between the scapula, where the voluntary effort is initiated, and the supports, are not necessarily constrained by additional physical supports, such as back or chest rests. Now, the maximal operating force is known to depend on this factor: for instance, maximal isometric push force exerted at shoulder level by seated subjects is doubled when a back rest is placed at the shoulder instead of sacral level [6]. Such results point at the role played by the postural chain, here located between the scapula, the seat and the ground. In particular, biomechanical requirements must be fulfilled, given that the magnitude of the external force is directly proportional to the moment arm of the body weight couple. In other words the external force variations are proportional to the variations of the distance between the centre of pressure (CoP) and the centre of gravity (CoG), which has been proven theoretically and checked experimentally [3,6,7,18].

The influence of postural muscle fatigue on the control of global efforts has been poorly documented, since the study of Hellebrandt et al. [9] on the progressive irradiation of muscular activity. Most studies referred to postural stability following fatiguing lower limb efforts [1,5,8,14,15].

The question which is addressed is to determine whether global efforts can stop as a direct consequence of postural muscle exhaustion, using a joint electromyographical and biomechanical approach. To this end, in addition to the external force and CoP position, the primum movens and postural muscle electromyograms (EMGs) were considered, during submaximal isometric push efforts sustained until exhaustion.

Subjects were asked to sit upright on an adjustable seat, with the thighs horizontal and legs vertical, the upper limbs stretched out horizontally, and the hands lightly gripping a bar located at shoulder level (Fig. 1). They did not use a

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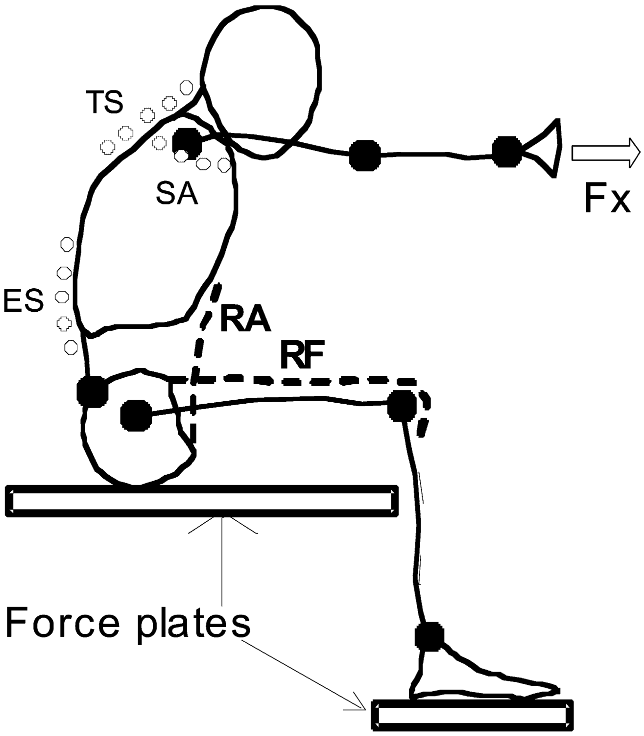

Fig. 1. Experimental paradigm. Subjects were asked to perform pushes, sitting in the reference position, with contact between the seat and the thighs covering 100% of the ischiofemoral length. The force exerted on the bar was measured along the antero-posterior axis (Fx). A custom-designed device, composed of three force plates linked by a rigid frame, was used to measure the global centre of pressure (CoP) displacement along the antero-posterior axis (Xp). EMGs were picked up from the primum movens (SA, serratus anterior) and four postural muscles (TS, trapezius superior; ES, erectores spinae; RA, rectus abdominis; RF, rectus femoris). Exhaustion occurs in RA and RF (broken lines).

backrest, and contact between the seat and the thighs covered 100% of the ischiofemoral length. Once the pre-push position was appropriate, the subjects were asked to exert two or three brief (2–3 s) maximal voluntary contractions (MVC), separated by 180-s rest intervals, in order to avoid any risk of fatigue. Then, they were asked to perform one push, from zero up to 75% MVC as rapidly as possible, to maintain this force level as long as possible, and to continue the effort until exhaustion. The force signal was displayed on an oscilloscope.

Force transducers were used to measure the force (Fx) exerted by the subjects on the bar along the antero-posterior axis. The seat was a custom-designed device, composed of three force plates (Fig. 1) linked by a rigid frame [3], which measured the CoP position along the antero-posterior axis (Xp). In addition, electromyographic signals (EMGs) were picked up from the dominant side by bipolar surface electrodes placed longitudinally along the muscle fibres. Inter-electrode impedance was less than 5 kΩ. The EMGs were amplified using differential amplifiers (frequency bandwidth from DC to 10 kHz). The muscular synergy associated with pushing includes several muscles throughout the body, as shown by Le Bozec et al. [12]. Preliminary experiments [11] were used to select representative muscles for each subject: (a) the primum movens (serratus anterior, upper fibres: SA), which moves the scapula in a forward movement of the shoulder and arm; and (b) four postural muscles, that is: a shoulder fixator (trapezius superior: TS) which is antagonist to SA, a lumbar and thoracic spine extensor (erectores spinae at the L4-L5 level: ES), a trunk flexor (rectus abdominis: RA), and a hip flexor (rectus femoris: RF), which is also a knee extensor.

The individual raw EMGs were digitized with a sampling rate of 1000 Hz. The CoP position and EMG records from each experimental session were aligned according to the onset of push force, and then averaged, as was the push force. In addition to push force and CoP position, root mean square (RMS) and mean power frequency (MPF) were calculated over 2-s intervals from the push onset to its end: a shift of MPF towards low frequencies was taken as a sign of muscular fatigue, if it was not accompanied by a decrease in the corresponding RMS value. In order to allow comparisons between subjects, the RMS and MPF values were expressed as a percentage of the values they displayed at the onset of the 75% MVC effort. The processed data were analysed using a one-way repeated measures analysis of variance technique. The scatter diagrams between EMG and biomechanical parameters were approximated by linear correlations, and the Pearson correlation coefficient (r) was used to test the strength between variables. Slopes (a) and standard errors (S.E.) were calculated for each. Data were considered significantly different when the probability of error was 0.05 or even less ($P < 0.05$: significant; $P < 0.01$: very significant; $P < 0.001$: highly significant).

Five right-handed male adults participated in the experiments. None of them had a history of neurological or musculoskeletal disorder. Subjects gave their informed consent and the experiments were conducted in accordance with legal requirements (Huriet law).

The results showed that the MVC push force was 67.8 ± 13.6 N. The 75% MVC push force (50.8 ± 10.2 N) was sustained for 180–360 s, depending on the subject (mean = 288 ± 78 s), after T0, the onset of the effort (Fig. 2). This duration corresponded to 30% of the effort total duration, and was referred to as the 'endurance period'. Xp position was approximately constant as well (−84 ± 16 mm, i.e. backwards with respect to the pre-push position). However, RMSs began to increase above their reference level, as soon as 2–3 s after push onset (Fig. 2). They continued to increase until the end of the period (T30). Depending on the muscle, the RMS increase was either very or highly significant (Table 1). Moreover, the power spectrum moved toward lower frequencies: all the MPFs decreased in a significant manner, either significantly, or very and highly significantly.

Then, Fx began to fall, and Xp to return to its pre-push rear position. The decrease lasted until complete exhaustion (T100), and the period was referred to as the 'exhaustion period'. Complete exhaustion occurred 720–1020 s after

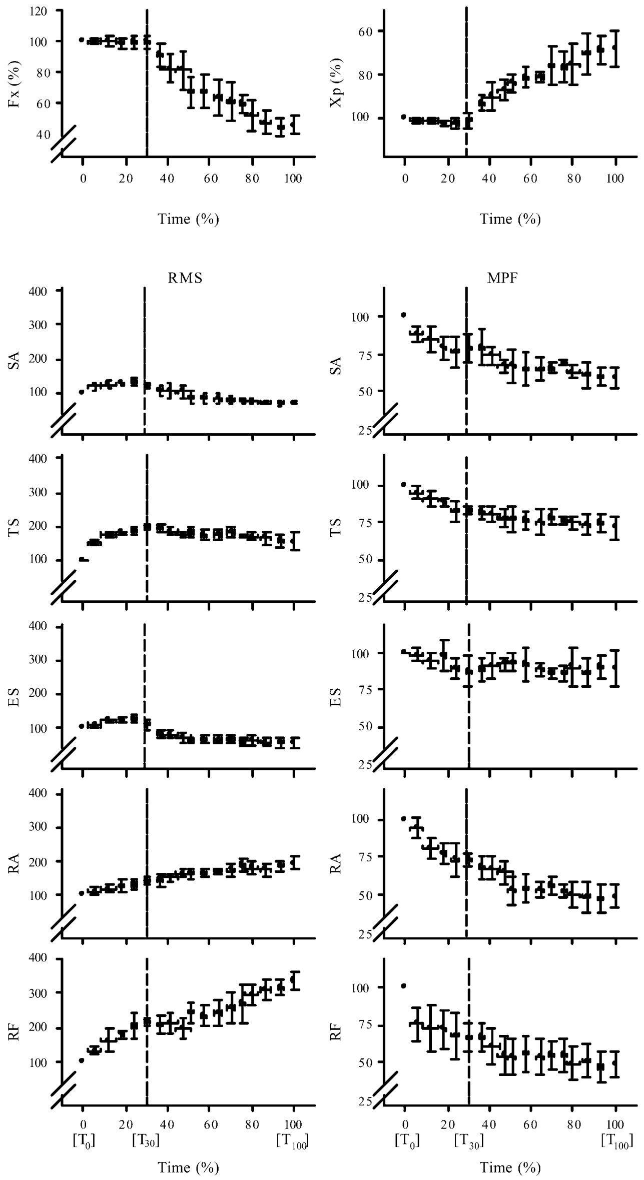

Fig. 2. Biomechanical and EMG parameters as a function of time, from the onset to the end of the push effort. Upper row: horizontal push force (Fx, as a percentage of the 75% MVC force) and CoP antero-posterior displacement (Xp, as a percentage of its position at the 75% MVC force) plotted against time (as a percentage of the total time). Lower rows: root mean square (RMS, left columns) and mean power frequency (MPF, right columns) plotted against time (as a percentage of the total time). SA, serratus anterior; TS, trapezius superior; ES, erectores spinae (L4–L5); RA, rectus abdominis; RF, rectus femoris. Fx, Xp, RMS and MPF were calculated over 2-s intervals. The diagrams represent the means and standard deviations of five subjects.

the onset of the effort, depending on the subject (mean = 900 ± 120 s). At this time, Fx ranged between 40 and 50% of the 75% MVC reference value (Fx = 45.5 ± 5.7%), and the Xp recoil was between 56.4 and 77.8% (Xp = −55 ± 10 mm, i.e. 67.8 ± 8.0%). The correlation between the CoP antero-posterior position and external force decrease ($r = 0.78$) was highly significant, and the slope of the regression line (a) indicated proportional variations ($a \approx 1$).

During this period, all the muscles under consideration remained activated. However, the fatiguing process did not induce the same EMG changes in the various muscles (Fig. 2). Indeed, in SA, the push primum movens, the RMS and MPF decreased highly or very significantly (Table 1). The postural muscles yielded two different behaviours. On the one hand, RA and RF displayed a very significant RMS increase (greater for RF than for RA: $t = 9.34$, $P < 0.001$), while their MPFs showed a very significant decrease. On the other hand, TS displayed a significant RMS decrease and ES a highly significant one, while the MPF decrease was highly significant in TS, and was not observed in ES.

In order to compare EMGs with the push force variations, the RMS data were expressed as a function of Fx (Table 2). All the RMS/Fx linear correlation coefficients were highly significant and the slopes very significantly different from zero: the RMS increased (RA, RF), or decreased (SA, TS, ES), in relation to Fx decrease. In addition, the RF increase was steeper, and RA increase less steep than the Fx decrease; the TS and ES decreases were less steep than Fx; and the SA decrease was proportional to the Fx decrease ($a \approx 1$).

The most striking feature of the study refers to postural muscle activation (RA and RF), as compared to primum movens (SA) activation, when push force decreases. A joint biomechanical and EMG argument is helpful in interpreting the data.

In their study of non-fatiguing pushes, Gaughran and Dempster [6] established theoretically, and checked experimentally, that maximal force is proportional to the antero-posterior distance between CoG and CoP. CoG forward displacement (with respect to the pre-push position) is associated with a typical forward bending of the trunk, and CoP backward displacement, to a backward rotation of the lower trunk and pelvis. In addition, it was shown in maximal push efforts [3] that CoP displacement is great (108 mm), unlike that of CoG (5 mm), which warranted limiting this study to CoP displacement.

These biomechanical features result from a complex synergy between focal and postural muscles, which has been described in the absence of fatigue [12]. Indeed, to develop an efficient isometric push, SA, the primum movens requires thoracic fixation. RA contraction provides this fixation. In addition, RA flexes the trunk and tends to rotate backward the structure composed of the lumbar spine and pelvis; this structure is mobile in relation to an axis passing through the femoral heads when contact with the seat is complete, as in this study [16]. RF opposes this action, in that it pulls the pelvis forward. In addition, as its insertion at the knee level is not fixed, it flexes the thigh, decreasing ischiofemoral contact with the front of the seat, and consequently moves effective seat contact to the rear. Lastly, TS and ES, respectively SA and RA antagonists, contribute to a stiffening of the thoracic and lumbar spine, with ES contracting in order to allow the hypolordotic lumbar spine position associated with the initial posture. To limit

Table 1
Root mean square (RMS) and mean power frequency (MPF)

	SA	TS	ES	RA	RF
T30/T0					
RMS (%T0)	135.1 ± 13.3	188.6 ± 11.5	125.6 ± 11.2	129.7 ± 16.5	204.8 ± 34.9
$F(1,5)$	34.7***	298.5***	24.9**	16.2**	45.0***
MPF (%T0)	77.3 ± 9.0	82.4 ± 6.5	89.4 ± 7.5	73.0 ± 11.4	68.3 ± 15.7
$F(1,5)$	31.4***	35.8**	9.8*	28**	20.3**
T100/T30					
RMS (%T0)	66.8 ± 4.4	154.2 ± 24.6	51.1 ± 16	193.6 ± 17.7	334.5 ± 28.7
$F(1,5)$	117.9***	6.5*	62.9***	30.6**	22.8**
MPF (%T0)	59.4 ± 7.1	71.0 ± 8.1	89.1 ± 11.9	48.8 ± 7.9	48.5 ± 9.4
$F(1,5)$	12.2**	113.8***	0.001°	18.2**	28.0**

SA, serratus anterior; TS, trapezius superior; ES, erectores spinae (L4–L5); RA, rectus abdominis; RF, rectus femoris. T30/T0: comparisons between the push onset (T0) and the end of constant effort (T30). T100/T30: comparisons between the push decrease onset (T30) and the end of the effort (T100). In order to allow comparisons between subjects, the RMS and MPF values were expressed as a percentage of their maximal values displayed at the onset of the 75% MVC effort (% T0). °$P > 0.05$: not significant; *$P < 0.05$: significant; **$P < 0.01$: very significant; ***$P < 0.001$: highly significant.

the interpretation to main biomechanical aspects, it may be considered that rectus abdominis favours the forward CoG position, as it flexes the trunk, and rectus femoris moves CoP to the rear, as it flexes the thigh. Hence, they both contribute to the removal of CoP from CoG, to which the maximal force was shown to be proportional [6].

These data, limited to a representative sampling of muscles, show that the push force decrease results from EMG variations in the primum movens as well as in the postural muscles. The endurance period does not raise major interpretation problems: since force is constant, a MPF shift towards lower frequencies, associated to an RMS increase, can be considered a sign of muscle fatigue [4]. Therefore, it is considered that both the primum movens and postural muscles display fatigue features. During the exhaustion period, the question is where the fatigue process is developing to such an extent as to cause complete exhaustion to occur so rapidly. It appears that the muscles under consideration present two different behaviours.

The primum movens, SA, might be considered to carry on the fatigue process, insofar as the MPF decline is less rapid than force decrease, which would exclude fatigue recovery. However, the RMS decline is proportional to that of the Fx ($a \approx 1$). Now, when a backrest is placed at shoulder height, maximal push force equals 400 N [2,5] and is much lower (approximately 68 N) when no back support is used, as in this situation. In other words, the force exerted by SA, the push primum movens, is largely submaximal (75% MVC ≈ 51 N). Consequently, an increase in RMS might be expected in order to oppose the fatigue development process. As this is not the case, the results cannot support the hypothesis that effort ceases because SA is exhausted.

At exhaustion, RMS values are increased in RA and RF, as compared to their value at the endurance time and even more at the onset of the constant push effort (Table 1): motor unit recruitment (and firing frequency) increase(s) continuously when push force decreases, in agreement with Stephens and Taylor [17]. As EMG fatigue characteristics are observed when the force level is above 15–20% MVC [13], it can be supposed that the force developed by RA and RF is at least above this threshold. Moreover, as their MPFs are declining drastically (more than 50%), it can be considered that these EMG features are the expression of severe muscle fatigue. In other words, it can be supposed that exhaustion occurs in these postural muscles. On the contrary, TS and ES, the other two postural muscles, do not appear to behave in the same way as RA and RF. Indeed, the

Table 2
RMS versus push force (Fx)

Plot	a	S.E.	r	a ± 1.96 S.E.	a variation	ΔRMS variation
SA/Fx	0.968	0.088	0.83***	$0.796 < a < 1.140$	$a \approx 1$	ΔSA ≈ ΔFx
TS/Fx	0.479	0.116	0.49***	$0.252 < a < 0.706$	$0 < a < 1$	ΔTS < ΔFx
ES/Fx	0.506	0.102	0.56***	$0.307 < a < 0.705$	$0 < a < 1$	ΔES < ΔFx
RA/Fx	−0.716	0.110	0.64***	$-0.501 < a < -0.931$	$0 < a < -1$	ΔRA < ΔFx
RF/Fx	−2.035	0.276	0.71***	$-1.495 < a < -2.575$	$a > -1$	ΔRF > ΔFx

SA, serratus anterior; TS, trapezius superior; ES, erectores spinae (L4–L5); RA, rectus abdominis; RF, rectus femoris. The scatter diagrams were approximated by a linear correlation. The RMS/Fx slopes (a) and slope standard errors (S.E.) were calculated for each muscle. r, Bravais–Pearson coefficient of correlation; a ± 1.96 S.E. defined the confidence limits (95% of the observations were included). The RMS/Fx regression slopes could be considered different from zero, or different from one, when this figure was not included within the confidence limits. The last column indicates whether the RMS variations (ΔRMS) are greater than, less than, or equal to the Fx variations (ΔFx). ***$P < 0.001$: highly significant.

results they display are similar to those of the SA. Therefore they refrain from considering that TS is exhausted at the end of the effort, and exclude that any ES fatigue process is in progress.

To stress that postural muscles controlling the pelvic girdle, i.e. RA and RF, make a major contribution to global efforts is in agreement with their biomechanical action. Indeed, when the external force decreases as a consequence of exhausting effort, the CoP and CoG tend to return progressively to the pre-push position: the CoP forward displacement is moved back by 29 mm (about 32.2% with respect to its pre-push position), while the CoG backward displacement is limited to a few millimetres (according to preliminary data). In other words, the antero-posterior distance between CoP and CoG decreases, in accordance with previous results [10]. Therefore, in order to maintain the prescribed push force, it is necessary to preserve as much as possible the antero-posterior distance between CoP and CoG. The continuous RA and RF activation increase during the exhausting process tends to preserve the required distance between CoG and CoP, and in particular the CoP rear position. Clearly, RF plays a major role resulting from its actions on the hip and knee, explaining its drastic EMG increase. Both actions are responsible for the CoP position, as shown by the correlation coefficient between RMS and Xp ($r = 0.82$). The strength of the relation between RA and Xp is lower ($r = 0.64$), which is likely related to its role in the forward bending of the trunk, i.e. in CoG position.

To conclude, it is suggested that the effort stops as a consequence of postural muscle exhaustion. Postural muscles make a major contribution to global efforts, in that they allow compliance with biomechanical requirements, in particular in preserving the distance between the centre of pressure and the centre of gravity, which must be proportional to the external force. More generally, these results stress the influence of the working capacity of the postural muscle in global efforts.

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