

# Anticipatory postural adjustments depend on final equilibrium and task complexity in vertical high jump movements

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## Abstract

Anticipatory postural adjustments (APA) associated with high vertical jumping were studied in five normal men. The dependence of APA on final equilibrium and task complexity was studied by analyzing the characteristics of single versus repetitive jumps. Subjects performed series of 25 single jumps and 25 repetitive jumps on a force platform, in response to a Go signal. Surface EMG from the Soleus (SO), Tibialis anterior (TA), Vastus lateralis (VL) and Biceps femoris (BF) muscles were recorded simultaneously with the three components of the ground reaction forces.

The existence of APA associated with both single and repetitive jumps was evidenced by a backward shift of the center of pressure, an SO deactivation, and a TA activation which preceded the onset of movement by hundreds of milliseconds. In repetitive jumps, SO deactivation occurred later than in single jump, whereas the center of pressure shift started earlier, lasted longer and had a greater amplitude. Moreover, repetitive jumps were initiated later with respect to the Go signal.

These data show that the central nervous system anticipates not only the equilibrium disturbance caused by an initial movement but that caused by a whole sequence of movements. They also show that the corresponding APA are based heavily on a single functional ankle synergy. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords:* Posture; Jump; EMG; Motor control; Repetitive task

## 1. Introduction

Anticipatory postural adjustments (APA) are associated with fast voluntary movements. This notion has been supported by a great number of studies on the upper limb [5–7,25,20,21], lower limb [27,33,18,32,30] or trunk movements [14,15], as well as by work on certain whole body movements in which there was essentially a forward [10,13,8,17,26] or an upward [36,37] progression of the subject's center of gravity.

The main role of the APA associated with limb or trunk movements is to preserve the whole body balance by compensating in advance for the postural disturbance produced by movement; whereas the role of the APA associated with gait initiation is to create the disequilibrium which is necessary to initiate movement [9,10,26].

Most studies have revealed that when attempting to minimize balance perturbation, the central nervous system takes into account the biomechanical characteristics of the programmed movement, but also those of the initial and final equilibrium [27,31,18,32,23,29].

In natural life, movements are rarely isolated. Thus it is important to know if the central nervous system anticipates only the equilibrium disturbance caused by the first movement or if it anticipates a whole sequence of movements.

The idea that postural adjustments could anticipate not only the initial movement but also those that proceed it seems plausible on the basis of psycho-physiological studies, which have shown that the reaction time is greater for a task made up of serial movements than for a task limited to a single one [22,12,19]. It is also known that the characteristics of the second movement of a serial task influence execution and motor programming [28,38,1,35,2], which means that the APA could not be programmed as a function of the first movement only. Further indirect arguments in favor of the APAs having

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a major anticipatory function can be seen in the results of studies on gait initiation. In the anticipation phase of gait initiation, postural changes are modulated as a function of the velocity of the forthcoming stable gait [10] and not as a function of the first step velocity only.

The present study was designed to answer two questions: 1) can the existence of APA be expanded to an upward-oriented, whole body movement which necessitates a loss of contact of the body with the ground: the vertical high jump? and 2) if APA do occur, are they the same for a single jump and for a series of three repetitive jumps?

## 2. Materials and methods

The experiments were performed on five male subjects ranging in age from 22 to 29 years, all of whom gave informed voluntary consent to participate in the experiments. None of them were experts in the task being studied.

The experimental procedure involved two kinds of jumping. The first jumping task consisted of series of Single Jumps (SJ). The second was a series of three Repetitive linked-up Jumps (RJ). Each series of vertical jumps had 25 trials, and subjects were instructed to jump at both a spontaneous (SJA) and maximum (MJA) jump amplitude. The two series were separated by a 15 min period of rest.

The initial posture was the same for both the single and repetitive jumps. Subjects were told to keep their hands clasped behind their back, their head and trunk as vertical as possible and their knees flexed at 30° compared to full extension. All vertical jumps were initiated from this “semi-squat position” to avoid countermovements [4].

Jump verticality was especially important, so subjects were instructed to pay particular attention to the head and trunk verticality during the jump and to land at about the same place on the platform. Trials in which these instructions were not respected were rejected.

Subjects had to jump following a visual signal which was given by a light-emitting diode placed at eye-level 3 m in front of them. This Go signal was preceded by a preparatory auditory signal. Time interval between preparatory signal and Go signal was randomized. Subjects were asked to jump as quickly as possible after the Go signal.

EMG activities from Soleus (SO), Tibialis anterior (TA), Vastus lateralis (VL) and Biceps femoris (BF) muscles were simultaneously recorded from the right side of the body by means of bipolar surface electrodes (Pellet Meditrace). The inter-electrode distance was 2 cm and the electrodes were placed over the muscles after gentle abrasion of the skin surface to reduce the inter-electrode electrical resistance to less than 10 k $\Omega$ . The

ground electrode was made of a large rectangular sheet of silver/silver-chloride strapped over the left wrist with a Velcro band. The myoelectric signals were amplified and filtered by means of differential amplifiers with identical bandwidth of 10–500 Hz.

The experimenter helped the subject maintain the knee angle during initial posture, by looking at the signal delivered by an electrogoniometer (M180 Penny and Giles) which was attached to the right lower limb of the subject at knee level.

The subjects stood barefoot on two force platforms (OR6–1000 AMTI), whose resonance frequency was greater than 500 Hz. The platforms were used to record the ground reaction forces under each foot in three orthogonal directions, antero-posterior (Ry), lateral (Rx) and vertical (Rz), and to calculate the corresponding moments (My, Mx, Mz). The signals were amplified with a bandwidth of 0–1050 Hz. This bandwidth largely covers that of the signal (0–250 Hz). The antero-posterior displacement of the Center of Pressure (CPy) was calculated according to the equation  $CPy = Mx/Rz$ .

The vertical jump impulse was obtained by integrating the vertical reaction force (Rz) over the duration of the vertical acceleration phase of the body, which stopped when the foot took off from the platform.

EMG and mechanical signals were sampled at 1000 Hz. The samples were digitized by a 16 bit converter and stored on a PC disk.

Timing and amplitude of EMG changes and dynamic events were subjected to several statistical analyses: Descriptive Statistics, Spearman correlation and the Student *t*-test for independent groups completed with the Mann and Whitney non parametric test. These analyses were made in order to compare data obtained with single jumps and repetitive jumps, but also when it was necessary to compare the MJA and SJA data or inter-subject data. Throughout Section 3, the values presented are mean values  $\pm$ SD, and a confidence interval  $P \leq 0.05$  is considered as significant.

## 3. Results

Figs. 1 and 2 show examples of EMG and dynamic activities obtained for single and repetitive jumps. EMG and dynamic activities obtained respectively for single jumps (SJ) and repetitive jumps (RJ) were compared.

Since vertical jump amplitude is directly proportional to jump impulse [24], the latter parameter was used to give a rough description of performance.

In single jumps, the mean value of the vertical jump impulses was significantly greater than for repetitive jumps (73 $\pm$ 14 N.s. vs 63 $\pm$ 19 N.s.). In order to allow a valid comparison between single and repetitive jumps, trials in which impulse values were not in the same range in SJ and RJ were rejected. Then, an equal number of

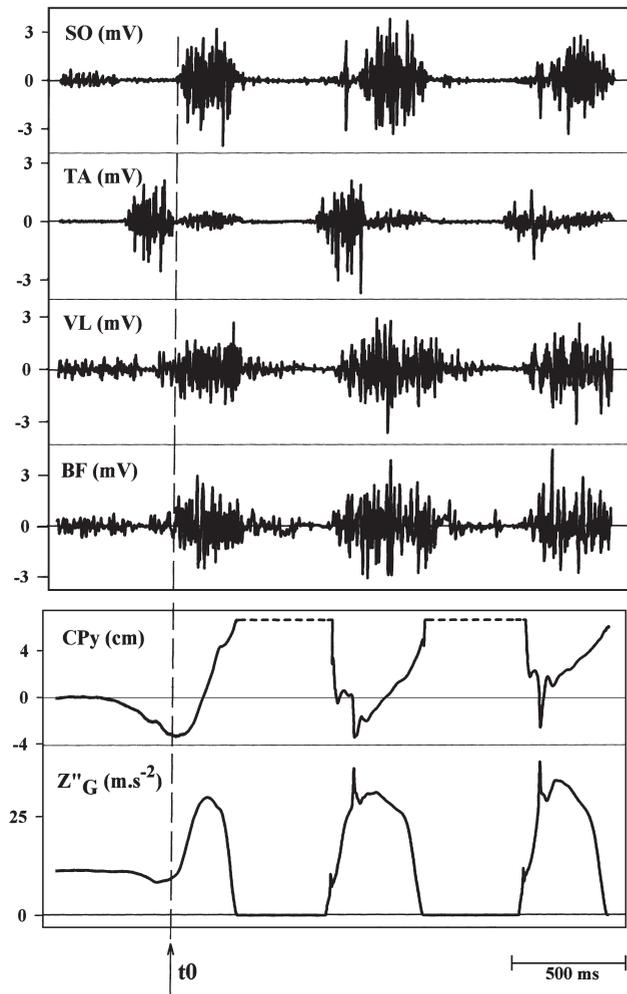


Fig. 1. EMG pattern, CP backward shift and CG vertical acceleration of repetitive high vertical jumps. The vertical dotted line indicates the soleus burst onset ( $t_0$ ). The first jump was preceded by a large soleus deactivation, a tibialis anterior activation, a center of pressure backward shift and a depression of vastus lateralis and biceps femoris EMG. Soleus (SO), tibialis anterior (TA), vastus lateralis (VL) and biceps femoris (BF), CPy: displacement of the center of pressure in the antero–posterior direction,  $z''_G$ : vertical acceleration of the center of gravity. Data from one subject.

remaining SJ and RJ trials were grouped under two vertical impulse classes: maximal jump impulses (corresponding to MJA) and spontaneous jump impulses (corresponding to SJA). Thus, vertical impulse values for MJA were  $77 \pm 14$  N.s. for the single jump task and  $76 \pm 17$  N.s. for the repetitive jump task. The vertical impulse values for the SJA were  $65 \pm 11$  N.s. in SJ and  $62 \pm 15$  N.s. in RJ. Finally, at the end of this analysis vertical impulse values for all the jumps taken into consideration were  $71 \pm 14$  N.s. for SJ and  $69 \pm 19$  N.s. for RJ.

It must be noted that the quantitative analysis applied to repetitive jump tasks was restricted to the first jump of each trial.

Heel-off was preceded by a Soleus EMG burst, the

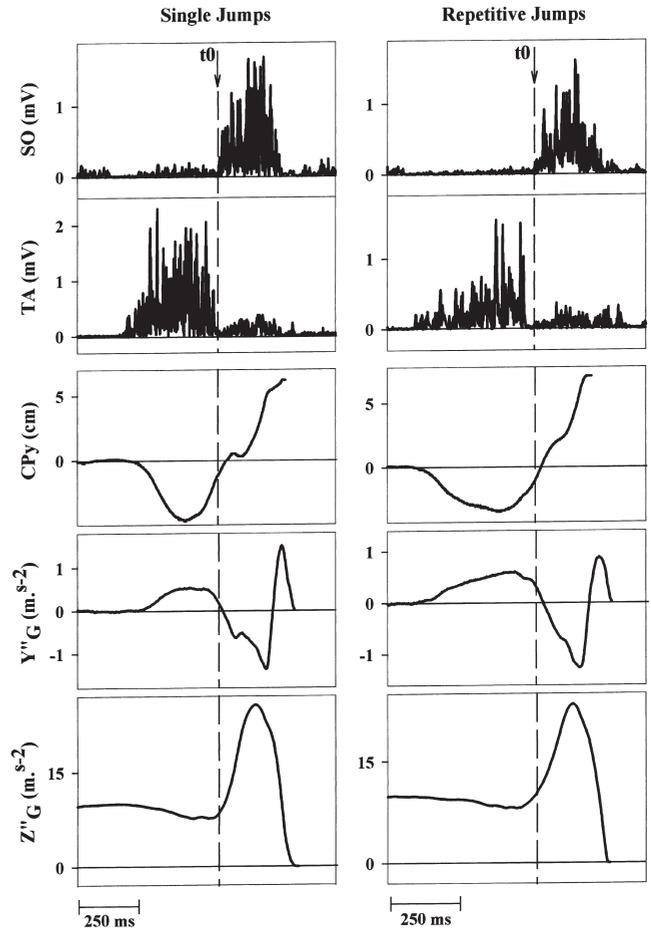


Fig. 2. Comparison of EMG and biomechanical traces between single high jump and the first jump of a repetitive series. The vertical dotted line indicates the soleus burst onset ( $t_0$ ). From top to bottom: rectified EMG of soleus (SO) and tibialis anterior (TA), displacement of the center of pressure (CPy), anteroposterior ( $y''_G$ ) and vertical accelerations ( $z''_G$ ) of the center of gravity. CPy trace is interrupted at the onset of the flying phase because CPy cannot be calculated in the absence of body contact with platform. This is represented on the corresponding traces by horizontal dashes. Jumps performed at a spontaneous amplitude.

onset of which was taken as the onset of voluntary movement. This time was taken as time zero ( $t_0$ ) for all measurements, with negative and positive signs indicating a time before or after  $t_0$  respectively.

The onset of voluntary movement with respect to the visual Go signal occurred earlier in SJ than in RJ (Table 1). On the other hand, the SO EMG patterns were similar in both experimental conditions. In the initial semi-squat posture, SO EMG showed a tonic activity. Then, a more or less marked deactivation was consistently identified. It was significantly earlier for SJ than for RJ: a drop in SO EMG amplitude occurred  $-459 \pm 152$  ms before  $t_0$  in SJ and  $-369 \pm 103$  ms in RJ. Following SO deactivation, a Tibialis anterior excitation occurred with a latency which did not differ between the two experimental conditions ( $-316 \pm 122$  ms vs  $-322 \pm 101$  ms with respect to  $t_0$ ). Because SO deactivation appeared earlier in single

Table 1

Summary of all the analysed EMG and biomechanical parameters for single and repetitive jumps<sup>a</sup>

Parameters	Single jump	Repetitive jump	P
Movement onset–SO burst (ms)	587±82	627±96	0.0003
SO deactivation latency (ms)	–459±152	–369±103	<0.0001
TA activation latency (ms)	–316±122	–322±101	NS
SO–TA delay (ms)	–148±112	–47±56	<0.0001
VL activation latency (ms)	–26±74	+3±48	<0.0001
BF activation latency (ms)	–36±68	–7±38	<0.0001
Impulse latency (ms)	+29±65	+50±53	0.0034
Rz peak latency (ms)	+162±45	+174±53	NS
Impulse duration (ms)	250±38	252±36	NS
Impulse (N.s.)	71±14	69±17	NS
CP shift latency (ms)	–236±88	–282±104	0.0001
CP shift peak latency (ms)	–47±66	–71±76	0.0045
CP shift duration (ms)	199±68	220±63	0.0115
CP shift amplitude (cm)	3.5±1.1	4.1±0.9	<0.0001

<sup>a</sup> Mean values±SD for all subjects and experiments, *P*=level of significance. SO burst onset was measured from the “go signal” and taken as  $t_0$  for the other latency measurements. Tibialis anterior latency was the sole parameter of the APA which did not depend on the jump modality: single or repetitive. Impulse values did not differ from one jump condition to another.

than in repetitive jumps, the interval TA–SO was shorter in RJ (Table 1).

Vastus lateralis and Biceps femoris EMG showed a more or less pronounced initial tonic activity accompanying the initial posture. A VL and BF excitation occurred shortly before or after the SO EMG burst and was very often preceded by a depression even a silencing of the initial tonic activity. VL and BF bursts of activity were closer to  $t_0$  in RJ and obviously earlier with respect to  $t_0$  in SJ. The onset times of the muscle activations were respectively  $-26\pm74$  ms for VL and  $-36\pm68$  ms for BF in SJ and  $+3\pm48$  ms for VL and  $-7\pm38$  ms for BF in RJ. In both conditions, VL and BF appeared to be more or less co-activated with the Soleus muscle.

The myoelectric activities of the agonist and antagonist muscles of the ankle displayed a strong time-linkage for each kind of vertical jump. The onset of SO deactivation and the onset of TA activation were linearly correlated (Fig. 3) with a more significant coefficient in RJ ( $r=0.850$ ) than in SJ ( $r=0.682$ ).

Thus, the same pattern of SO deactivation–TA activation was apparent in single and in repetitive vertical jumps and gave evidence for APA associated with vertical jumping.

The onset times of VL and BF bursts of activity were close together and correlated. All the correlation coefficients were significant but greater in SJ, with  $r=0.780$ , than in RJ, with  $r=0.541$ .

In the initial posture, the Rz trace was stable. Then it showed two phases before the take-off: the first phase corresponded to a negative acceleration, i.e. a lowering of the body or a “counter-movement” which was identified in 70% of SJ trials and in 89% of RJ trials. This first acceleration change occurred earlier in RJ than in

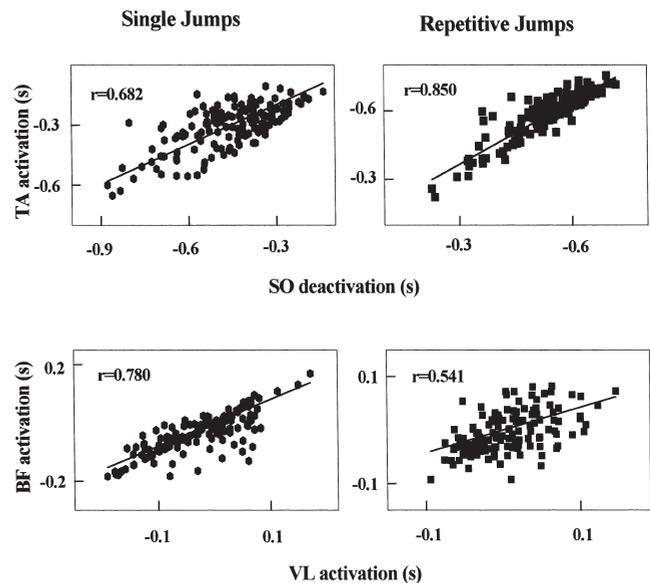


Fig. 3. Correlations between onset of soleus deactivation and onset of tibialis anterior activation (above), and between onset of biceps femoris activation and onset of vastus lateralis activation (below) for single and repetitive high jumps. Strong linkages were obtained between the EMG changes for single (left side) and repetitive (right side) jumps. Data from all the subjects and experiments.

SJ ( $-250\pm102$  ms vs  $-207\pm83$  ms with respect to  $t_0$ ). The second phase was a positive acceleration of the body allowing take-off and vertical flight. In SJ this phase started at  $+29\pm65$  ms after  $t_0$ , reached a peak at  $+162\pm45$  ms and lasted  $250\pm38$  ms. Similar values were obtained in RJ, except for the onset of the positive acceleration phase, which was significantly later than in SJ. The respective values were  $+50\pm53$  ms for the onset and  $+174\pm53$  ms for peak acceleration, with a duration of  $252\pm36$  ms.

In both single and repetitive jumps, CPy displacement analysis showed a preliminary dynamic change consisting of a backward shift followed by a wide and rapid forward shift until take-off. In repetitive jumping, the onset and the peak of the CP backward shift occurred earlier with respect to  $t_0$ , and the shift duration was greater (respectively:  $-282\pm 104$  ms,  $-71\pm 76$  ms and  $220\pm 63$  ms) than in single jumping (respectively:  $-236\pm 88$  ms,  $-47\pm 66$  ms and  $199\pm 68$  ms). The amplitude of the CP backward shift was also greater in RJ ( $4.1\pm 0.9$  cm) than in SJ ( $3.5\pm 1.1$  cm). Thus, the analysis of CPy displacement showed that APA associated with repetitive jumps were greater and more anticipatory than those associated with single jumps.

In both types of vertical jumps, the time of onset of the backward CP shift was strongly correlated with the duration (SJ  $r=-0.774$  and RJ  $r=-0.750$ ) and with the peak amplitude (SJ=0.601 and RJ=0.569) of the shift (Fig. 4). The shorter the CP shift duration was, the lower the anticipatory onset of the CP shift.

In both single and repetitive jumps, there was direct proportionality between the onset of SO and TA EMG changes and the onset of CP shift (Fig. 5). The onset of CP backward shift was correlated with the onset of SO deactivation and onset of TA activation.

The repetitive jumps showed a stronger linkage than the single jump. In RJ, the coefficient was  $r=0.825$  for the SO deactivation and the CP shift onset while that of the TA activation and the CP shift was  $r=0.970$ . In the same order, the coefficient  $r$  in SJ were 0.369 for the SO deactivation and the CP shift and 0.572 for the TA and the CP shift.

Thus, the data obtained for all the subjects and all the experiments showed that the CP backward shift

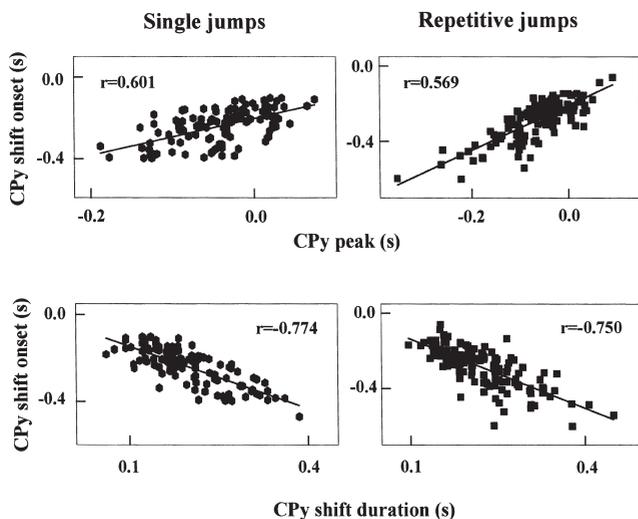


Fig. 4. Correlations between CP time parameters for single (left side) and repetitive (right side) jumps. The linkage between the onset of CP backward shift and the time of the CP peak was positive (above) and that between the onset and the duration was negative (below). Data from all the subjects and experiments.

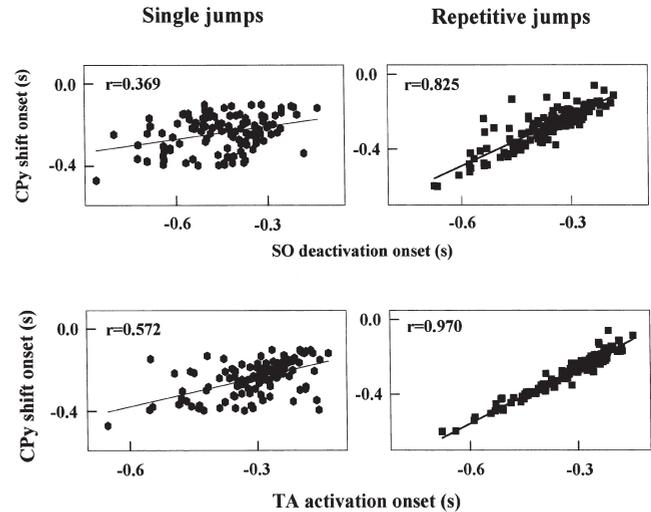


Fig. 5. Correlations between the onset of the center of pressure shift and soleus or tibialis anterior EMG changes latencies for single (left side) and repetitive (right side) jumps. The onset of the center of pressure shift was correlated with the latencies of soleus deactivation (above) and tibialis anterior activation (below). The linkage between SO deactivation or TA activation and CP backward shift was stronger in repetitive than in single jump. Data from all the subjects and experiments.

depended on the SO and TA excitation changes, whatever the jump modality (SJ or RJ).

In summary, APA associated with single and repetitive jumps share common qualitative characteristics: a deactivation of SO followed by a TA activation which mainly cause a backward CP shift. When compared to SJ, the first jump in a repetitive jump series shows that (Fig. 6): 1) SO deactivation occurs later, although TA activation onset is unchanged, which gives a shorter TA–SO delay; 2) the CP shift starts earlier with a longer duration but a larger amplitude; 3) Movement (i.e. SO EMG burst onset) starts after a longer delay with respect to the Go signal.

#### 4. Discussion

Although APAs are most often associated with fast voluntary movements, they can be absent when initial and final equilibrium is very difficult to maintain and balance could be endangered by the postural adjustments, as in the flexion–extension of the lower limb executed with the unipedal stance [32] or conversely, when initial and final conditions of equilibrium are stable and identical, as in tip-toe rising, if subjects are instructed not to remain standing on the toes [27]. They were also absent or greatly reduced when releasing a load was performed on a narrow support area [3]. Thus, for single vertical jumps, where initial and final posture are the same, the existence of APA remained to be demonstrated. It has been shown here that single and repeti-

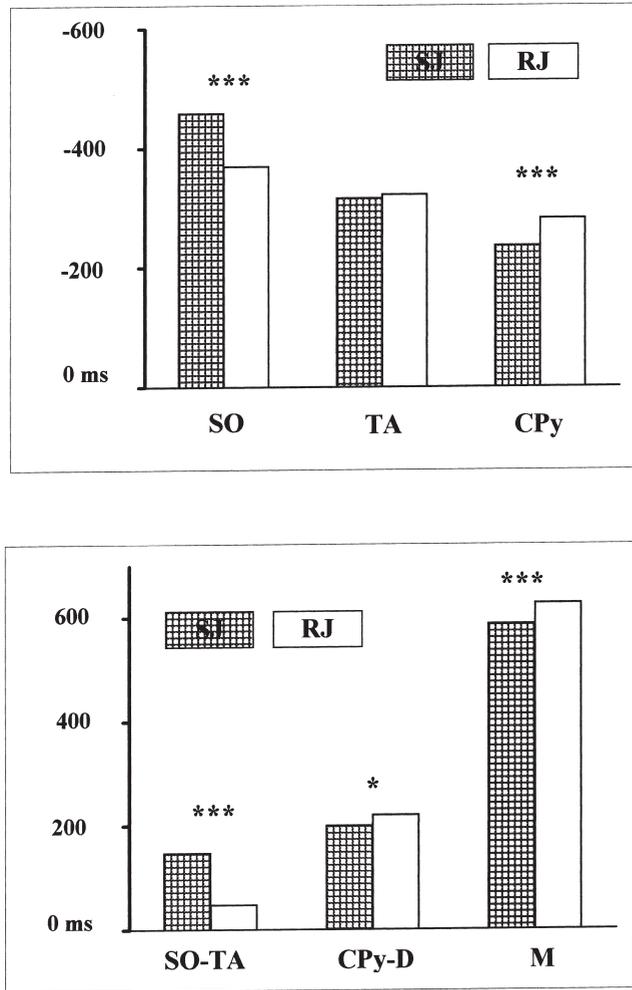


Fig. 6. APA timing in single (SJ) and repetitive (RJ) high jumps. Upper graph: Mean values of the onset times of soleus deactivation (SO), tibialis anterior activation (TA) and displacement of the center of pressure (CPy). Lower graph: Mean values of the soleus–tibialis anterior delay (SO–TA), duration of the CP backward shift (CPy–D), and time of the onset of the voluntary movement (*M*). Student *t*-test results were represented above the corresponding column pairs by means of star symbols. A confidence interval  $P \leq 0.0001$  is represented by three stars,  $P = 0.003$  by two stars and  $P = 0.01$  by one.

tive jumps were preceded by dynamic postural mechanical and EMG activities, thus attesting to the existence of APA. The first dynamic postural change was a backward shift of the CP which, as for gait or tip-toe initiation, was mainly based on a depression in Soleus activity, following by an excitation of Tibialis anterior. Because of the anatomical location of these muscles, their synergy may create a significant forward oriented ankle rotation moment and thus the required whole body disequilibrium. This does not signify that the SO–TA synergy fully determines the CP shift. In particular, it has been shown here that the VL and BF muscles, which were tonically activated to maintain the initial semi-squat posture, were very often more or less deactivated during the CP shift, before being phasically activated

simultaneous to the burst of SO activity. This depression of VL and BF activity probably contributes to CP shift and to the unloading phase, whereas their burst of activity could contribute to the upward impulse. Since similar synergies are at the basis of many forward oriented movements [27,13,10], the present results not only extend the existence of APA to upward oriented whole-body movements displaying a flying phase, but also the notion that simple synergies are at the basis of these APA.

Although simple and repetitive jumps share common APA characteristics, differences were found between the two jumping tasks: in repetitive jumping, the CP backward shift occurred earlier and its duration and amplitude were greater than for single jumps. It was also noticeable that in repetitive jumping, the depression in SO activity occurred later whereas the time of onset of TA phasic excitation remained the same as for single jumps, i.e. the time interval between SO and TA was shorter. Among others, the Lipshits et al. [27] and Kasai and Kawai [23] studies on tip-toe rising, and the Crenna and Frigo [13] study on gait initiation, have previously pointed out that the SO–TA synergy in APA was characterized by a stable chronology but also that the delay and amplitude of the activation changes was dependent on the initial posture (the degree of forward body or platform leaning) or the movement inertia [27,16]. In the present experimental conditions, special care was taken to help the subjects keep an identical initial posture from one trial to another. Thus, the adaptation of the APA was not attributable to differences in initial posture.

APA are also generally dependent on the biomechanical characteristics of movement (inertia, velocity). Since the single and the first jump of repetitive jumping were performed by means of similar vertical impulses, and reached similar heights, differences in the movement per se cannot be called upon.

Finally, APA differences between single and repetitive jumps could indicate that the programming of the first jump is different, i.e. takes into account differences in final equilibrium and/or differences in the programming of a single jump versus a series of repetitive jumps. Indeed, some studies have shown that the APA can be dependent on the final equilibrium: as an example, APA associated with a flexion–extension movement of the lower limb have a greater duration and amplitude for a final unipedal posture than for a bipedal posture, i.e. the APA are greater if final posture is less stable [18]. In our experiments, the final equilibrium at the end of the first jump in a series of three is dynamic, and must be programmed in order to control the lower limb stiffness, thus allowing a rebound in accordance with the intended jump height. Then, the increase in the APA duration and amplitude could more generally express the increase in difficulty of programming an efficient coordination between posture and movement. This hypothesis does

not exclude the other hypothesis, which is that the difference in APA between the two jump modalities could reflect the difference between programming a movement and a series of movements. It is well known that the reaction time increases with the complexity of the voluntary movement [19,11,34]. In our experiments, subjects had to jump following a visual Go signal. Nonetheless, they were instructed to pay special attention to the height and verticality of the jump, rather than jumping as soon as possible after the signal. Therefore, the time between the Go signal and the onset of Soleus burst ( $t_0$ ) cannot be considered as a true reaction time. Nevertheless this time was significantly shorter for single than for repetitive jumps, thus suggesting that the latter was a more complex task for the CNS, requiring a longer programming time, and it is plausible that at least part of the increase in programming duration was devoted to APA programming.

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