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# Anticipatory landing strategies differ between the lower and the upper limbs

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## 1. Introduction

Movement execution relies on a complex coordination controlled by the central nervous system (CNS). During voluntary movements, the CNS programs anticipatory muscular activations preceding predictable motor changes, based on an internal representation of both internal and external constraints (Wolpert and Kawato 1998). However, the functional role of these anticipatory activations remains unclear. In motor tasks with large momentum like landing, lower-limb muscular anticipations have been mostly characterized through co-activation patterns using EMG (Peng et al. 2011). According to these studies, muscular anticipations are thought to adjust muscular stiffness, to a level neither excessive nor insufficient, to avoid large joint angular velocities. This stiffness adjustment would serve a key purpose: slow down the center of mass velocity during ground contact (GC) to reduce the risk of functional instability and protect the skeletal system (Butler et al. 2003). However, the kinematic consequences of these anticipatory activations have been poorly described, and may clarify their functional role. Indeed, during both landing and drop-jumping, we found a knee flexion starting before GC (Bechet et al. 2023), and questioned whether this would be specific to the lower-limb.

When landing on the ground after a fall, humans often use their upper limbs for cushioning. Anatomical similarities between the lower and the upper limbs (i.e. three main joints allowing similar degrees of freedom) suggest they may be used similarly during landing. Anticipatory muscular co-activations were recorded in humans landing on their hands following externally-applied falls, with a slight elbow extension preceding GC, thought to prevent elbow buckling (Borrelli et al. 2020). However, this has not yet been verified in a voluntary landing context.

The aim of this study was to compare the kinematic consequences of anticipatory muscular activations in the upper limbs with that of the lower limbs when mobilized in a comparable landing task, before and after GC. We hypothesized that the anticipatory muscular activations would not provoke the same kinematic consequence between the elbow and knee

joints in anticipation, resulting in different landing coordination.

## 2. Methods

### 2.1 Participants & procedure

In a first experiment, 15 participants (7 females,  $25 \pm 4$  years old,  $173 \pm 8$  cm,  $67 \pm 8$  kg) landed on their feet from a 35 cm elevated platform on two force plates (Sensix) recoding the 3D ground reaction forces (GRF) at 2000 Hz. In a second experiment, 16 males ( $23 \pm 3$  years old,  $177 \pm 5$  cm,  $76 \pm 14$  kg) landed on their hands from a 35 cm elevated platform on the same force plates, with feet on the ground (Figure 1). Participants were instructed to keep their arms alongside their trunk, to limit shoulder abduction, and were allowed to familiarize with the task. A motion analysis system composed by 19 infrared cameras (Vicon) recorded at 200 Hz the 3D trajectories of 64 and 16 reflective markers, respectively.

### 2.2 Data analysis

GRF and marker trajectories were low pass filtered at 50 and 20 Hz, respectively, with a zero lag critically damped filter. For both experiments, flexion-extension angles were computed, and time-derived to obtain angular velocities. The onset of joint flexion was defined as the first instant during which the angular velocity was positive and GC was defined as the first instant when the vertical GRF exceeded 20 N. Rate of force development (RFD) was used to quantify the impact on the ground, defined as the variation of the vertical GRF over time, from GC to the first peak of vertical GRF. For each task, the trial with the lowest peak of vertical ground reaction force was analyzed.

### 2.3 Statistical analysis

Because they were all normally distributed, the dependent variables were compared between the lower and the upper-limb using an independent Student T-test, with a threshold set at  $p < 0.05$ .



Figure 1: Initial (left) and final (right) states of the upper-limbs landing task.

## 3. Results and discussion

The force results showed that the landing was globally similar, with smaller GRF when landing on the hands than on the feet (Fig. 2). Consecutively, the RFD was smaller for the upper limb ( $33.3 \pm 15.2$  BW.  $s^{-1}$ ) than for the lower-limb ( $82.9 \pm 61.1$  BW.  $s^{-1}$ ) ( $p < 0.01$ ). For the kinematics, the knee flexion started systematically before GC ( $-52 \pm 17$  ms), and before the elbow flexion ( $25 \pm 14$  ms after GC) ( $p < 0.001$ ). The angular velocity peak was larger and occurred sooner for the elbow joint

after GC ( $963 \pm 170 \text{ }^\circ \cdot \text{s}^{-1}$  at  $32 \pm 16 \text{ ms}$ ) compared to the knee joint ( $609 \pm 84 \text{ }^\circ \cdot \text{s}^{-1}$  at  $43 \pm 7 \text{ ms}$ ) ( $p < 0.001$  and  $< 0.01$  for the peak timing, respectively).

The aim of the study was to quantify the kinematic consequences of anticipatory muscular activations from the lower and upper limbs during landing. As hypothesized, the kinematic consequences were different in terms of joint angles and angular velocity for the knee and the elbow (Figure 2).

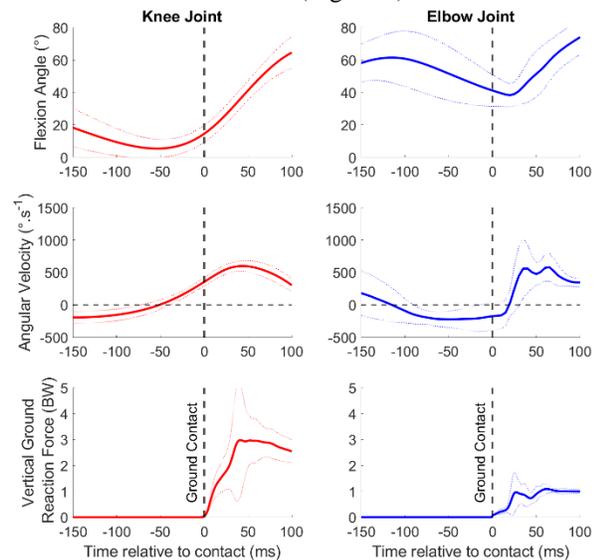


Figure 2: Results for the knee (left) and elbow (right) joints. Flexion angle (+) (top), flexion angular velocity (middle) and normalised vertical ground reaction force (bottom) during both tasks. Solid lines represent the mean and dotted lines represent one standard deviation. BW = body weight.

The anticipated knee flexion may be the reason why there was no abrupt change in the knee angle after GC (Figure 2): the knee flexion velocity increased smoothly, and was not modified despite the large GRF amplitude. This strategy probably allows to control a smooth lowering of the whole-body centre of mass and protects the knee joints (Bechet et al, 2023).

Similar to what was found in reactive hand landing (Borrelli et al. 2020), the elbow joint was extending before and at GC (Fig 2). However, contrary to the knee joint, the elbow angle displayed an abrupt change almost immediately after GC, resulting in a large elbow flexion angular velocity, and a large change of angular velocity. It was previously suggested that elbow extensors are largely activated before GC, to slow down the elbow flexion during GC and protect the head (DeGoede and Ashton-Miller 2003). This may explain why the elbow did not flex prior to GC. However, even if an anticipatory flexion was not achieved, and the mobilizing body mass was smaller compared to lower-limb landing, the upper-limb strategy still limited the impact force and the RFD, probably to protect the skeletal system from injuries.

The differences can also come from our protocol, with an unusual task performed with the upper-limbs, that can explain the large variations in the results. Moreover, the large angular velocity for the elbow joint suggest the upper limbs may not be suitable for this kind of task, with the absence of strong antigravity muscles compared to the lower-limbs.

## 4. Conclusions

Even though lower and upper limb anticipatory muscular activations may look similar at first glance, their kinematic consequences differ during landing. For the knee joint, the flexion that would have been induced by ground contact is anticipated, whereas an extension was recorded for the elbow joint. However, both seem to serve the same purpose: protect the skeletal system. This suggests that the CNS adapts the motor behavior to the anatomical constraints of each joint.

These specificities highlight that the kinematic consequences of muscular activations should be described when characterizing the motor consequences of anticipatory activations, to better describe how the CNS coordinates movements with large momentum.

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