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RESEARCH ARTICLE

The trampoline aftereffect: the motor and sensory modulations associated with jumping on an elastic surface

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Abstract After repeated jumps over an elastic surface (e.g. a trampoline), subjects usually report a strange sensation when they jump again overground (e.g. they feel unable to jump because their body feels heavy). However, the motor and sensory effects of exposure to an elastic surface are unknown. In the present study, we examined the motor and perceptual effects of repeated jumps over two different surfaces (stiff and elastic), measuring how this affected maximal countermovement vertical jump (CMJ). Fourteen subjects participated in two counterbalanced sessions, 1 week apart. Each experimental session consisted of a series of maximal CMJs over a force plate before and after 1 min of light jumping on an elastic or stiff surface. We measured actual motor performance (height jump and leg stiffness during CMJ) and how that related to perceptual experience (jump height estimation and subjective sensation). After repeated jumps on an elastic surface, the first CMJ showed a significant increase in leg stiffness ($P \leq 0.01$), decrease in jump height ($P \leq 0.01$) increase in perceptual misestimation ($P \leq 0.05$) and abnormal subjective sensation ($P \leq 0.001$). These changes were not observed after repeated jumps on a rigid surface. In a complementary experiment, continuous surface transitions show that the effects persist across cycles, and the effects over the leg stiffness and subjective experience are minimized ($P \leq 0.05$). We propose that these aftereffects could be the consequence of an erroneous internal model resulting from the high vertical forces produced by the elastic surface.

Keywords Stiffness · Internal models · Vertical jump · Perceptual illusion

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Introduction

When we walk, run or jump, our musculoskeletal system needs to adapt its stiffness according to the physical features of the surfaces, in order to store and restore elastic energy in the muscles and tendons (Cavagna 1977). Changes in stiffness have been modeled by a spring-mass model. According to this model, a single linear “leg spring” and a point-mass, equivalent to the mass of the body, can describe stiffness changes (Blickhan 1989). The stiffness of the leg spring represents the stiffness of the integrated musculoskeletal system (Farley et al. 1991, 1998; Farley and González 1996; Ferris and Farley 1997; Ferris et al. 1998; McMahon and Cheng 1990).

Many athletes include trampoline bouncing as part of their practice regimen in order to improve their balance and acrobatic skills (e.g. gymnastics, divers). By increasing leg stiffness on an elastic surface, humans reduce the average force required for jumping and, as such, increase the mechanical work done by the surface (Ferris and Farley 1997). Anecdotally, people report an intriguing and strong illusion when they attempt to perform a jump on the ground immediately after jumping on the trampoline. They report that their body is not able to detach itself from the floor and additional muscular effort is required to produce a jump from a non-elastic surface. We refer to this illusion as the trampoline aftereffect.

Perceptive illusions of gait and posture have been reported to be due to a sensory mismatch or sensory habituation (Lackner and Graybiel 1981; Pelah and Barlow 1996). However, to date, there have been no studies of the trampoline aftereffect. Indeed, it remains unclear if the aftereffect is related to changes in motor control, perception, or a combination of these factors. To address this question, we measured leg stiffness and jump height during countermovement jumps (CMJs) performed at maximal effort, as well as assessed perceptual judgments, after repetitive jumps on two different surfaces: a stiff surface (ground) and an elastic surface (trampoline). We investigated the extent to which motor and sensory adaptation can be influenced by changes in surface stiffness. We hypothesized that repetitive jumps on a trampoline would lead to perceptive as well as motor aftereffects during subsequent jumps on the ground.

Methods

Participants and general procedures

Fourteen healthy male subjects participated in this study [mean age: 19.57 ± 3.8; mean weight: 70.30 ± 12.9; mean height: 174.86 ± 7.6]. Participants were recruited from the Faculty of Sport Sciences of University of A Coruña and provided informed consent prior to participation. The experimental procedure was approved by the Ethics Committee of University de A Coruña.

Test jumps

The subjects were instructed to start in an upright position, rapidly squat, and then jump into the air with maximal effort. The hands were positioned on the hips throughout the test in order to eliminate the effect of arm swing during the performance of each jump. During the squat phase of the movement, the angular displacement of the knee was standardized so that the subjects were required to bend their knees to approximately 90 degrees. A 90 degrees knee bend was merely a reference value and not an excluding criterion. For a more detailed description about Test jumps (CMJs) performance see Bosco et al. (1983).

Perceptual judgments

After each CMJ performed on the force plate, the subjects made two perceptual judgments about their performance. First, they estimated the maximum height achieved (EH). The estimated height (EH) of the jump was normalized to the real height (RH). This ratio EH/RH provided quantitative information of accuracy (1 = maximal accuracy). In addition, the deviations from one indicate an estimation bias (values lowers than one is an underestimation of the height while values bigger than one is an overestimation).

Second, the participants were required to give a subjective rating of their performance. We used a perceptual scale similar to that used by Flanagan and Beltzner (2000). Used a 10-point scale, the subjects were asked to give a score, comparing the performance of the vertical jump to CMJs performed at the beginning of the session. A value of one represented a jump with the same perceptual sensations while 10 represented a jump with completely different perceptual sensations.

Adapting jumps (repetitive jumps)

During the adapting phase on the elastic and stiff surfaces, the subjects were required to jump keeping their hands on their hips. In order to equate the number and rate of jumps in both surfaces, the subjects jumped in synchronization with a metronome at a rate of 1 Hz. This was of importance since the jumping frequency has been shown to affect the leg stiffness (Farley et al. 1991; Hobara et al. 2010). This 1 Hz rate was chosen from pilot experiments that showed that this rate approximated that observed when people performed self-paced jumps on the trampoline.

In order to minimize muscular fatigue during the repetitive jumps, the subjects were asked to jump at low intensity.

Protocol

Main experiment

A week prior to the experimental sessions, subjects practiced the counter movement jump (CMJ). They were also trained to make the perceptual judgments.

Two experimental sessions were conducted, separated by a 1-week interval. In one session, the repetitive jumps were performed on an elastic surface (trampoline), and in the other session, on a stiff surface (ground). The order of these two sessions was counterbalanced.

Each experimental session started with a standardized warm-up protocol to ensure that the subject performed the vertical jumps with maximal effort without risk of injury. The warm-up ended with the subject performing three CMJs at maximal intensity on a force plate installed at ground level. After each jump, the subject was provided with feedback regarding the maximum height of the jump. This was the only feedback given during each experimental session. The subject then performed three more CMJs with an inter-trial interval of 30 s. We used the average of the three CMJs as a baseline (CMJ_{bsl}). After a 1-min break, the subject performed repetitive jumps (at 1 Hz) for 1 min on the selected surface (trampoline or ground). Immediately after the repetitive jumps, the subject performed six more maximal CMJs on the force plate (CMJ_1 to CMJ_6). After each CMJ, the subject was asked to make two perceptual judgments, one rating the maximum height achieved, and one rating the subjective experience. The subjects jumped inside an indoor facility with their eyes open and with their body oriented to the same direction at all times. Thus, the visual cues were kept constant.

Complementary experiment

We conducted a complementary experiment to examine repetitive effects of adaptation. Given that adaptation effects were most salient on the first CMJ after adaptation, we had participants alternate between bouts of repetitive jumping on the trampoline followed by a single CMJ on the ground. After the warm-up, the subject performed 3 CMJs on the force plate. We used the average of these as a baseline (CMJ_{BSL1}). The subject then completed 1 min of repetitive jumping on the trampoline, followed by a single maximal CMJ on the force plate. This cycle of 1 min adaptation followed by a single jump was repeated eight times, with each cycle separated by 1 min of rest. The CMJs are referred to as CMJ_{BK1} to CMJ_{BK8}. After the final cycle, the subject performed two more CMJs on the force plate without jumping on the trampoline (CMJ_{BSL2}, CMJ_{BSL3}). As in the previous experiment, the subject was asked to make the two perceptual judgments after each CMJ.

Apparatus and data analysis

The elastic surface was a trampoline fitted at floor level, with a surface of 3 × 1.5 m connected to 118 springs along the outer edge, resulting in a linear stiffness of 8.9 kN/m. The stiffness of the elastic surface was checked using static load tests (up to 2,000 N, see Arampatzis et al. 2001) in which weights were placed on the center of surface, and the displacement of the surface was measured (Ferris and Farley 1997). The linear regression between force and displacement was high ($r^2 = 0.99$). The stiff surface was a 50.8 × 46.4 cm force plate (AMTI, Newton, MA. Surface stiffness = 35,000 kN/m, see Ferris and Farley 1997).

All CMJs were performed on the force plate, and signals were sampled at 1,000 Hz. We computed vertical acceleration (from the ground reaction forces [GRF]) to obtain the vertical velocity and displacement of the center of mass [CoM] using the double integration method (Cavagna 1975). The height of the jump was obtained from the velocity value at the moment of takeoff using the following equation: $H = v^2/2g$ where v is the takeoff velocity and g the gravitational acceleration. Leg stiffness during the CMJ was defined as $F_{peak}/\Delta L$, where F_{peak} is the peak GRF (which correspond to the lowest position of the CoM), and ΔL is the vertical displacement of the CoM from the starting position to the lowest position (Ferris and Farley 1997; Liu et al. 2006; Fig. 1).

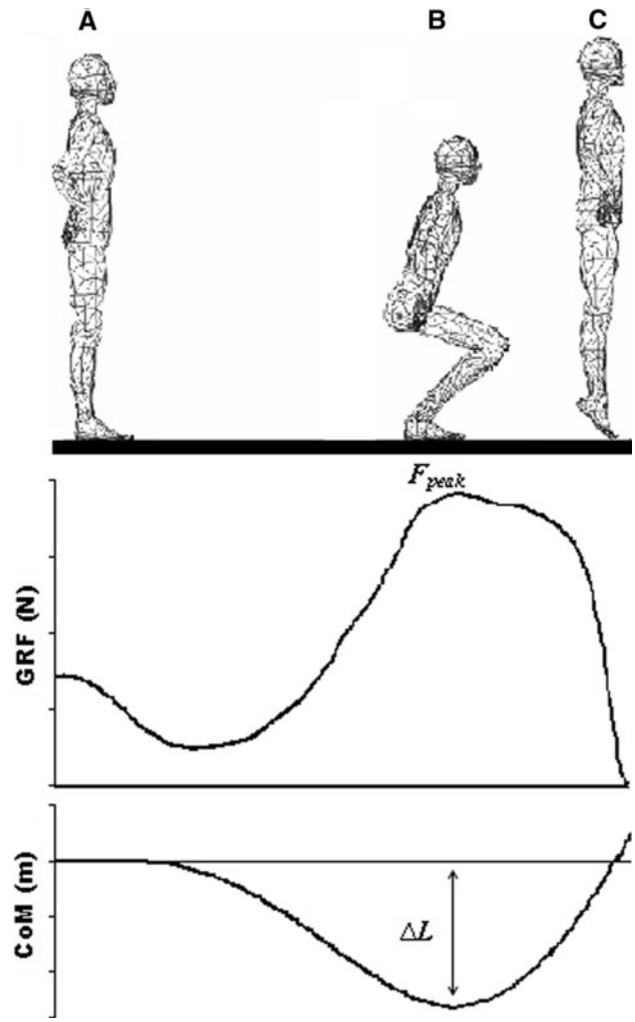

Fig. 1 Spring-mass model during vertical countermovement jump performed over a force plate. The figure shows different phases of the CMJ: **a** Initial position; **b** End of the squat movement; **c** Take off. Leg stiffness is calculated using the ratio between peak GRF (F_{peak}) and the *vertical* displacement of the CoM (ΔL) in the moment of its lower position

Statistical analysis

Two-way ANOVAs of repeated measures were performed with surface (elastic or stiff) and trial (CMJ_{bsl}, CMJ_1, CMJ_2, CMJ_3, CMJ_4, CMJ_5, CMJ_6) as factors. The ANOVAs were performed for the following variables: height, leg stiffness, F_{peak}, ΔL, and EH/RH ratio. For the analysis of the subjective experience, the trial factor was reduced to six levels (CMJ_1, CMJ_2, CMJ_3, CMJ_4, CMJ_5, CMJ_6) since CMJ_{bsl} was used as reference (value equal to one for all the subjects).

For the complementary experiment, one-way ANOVAs were performed with trial (CMJ_{BSL1}, CMJ_{BK1}, CMJ_{BK2},

CMJ_{BK3}, CMJ_{BK4}, CMJ_{BK5}, CMJ_{BK6}, CMJ_{BK7}, CMJ_{BK8}, CMJ_{BSL2}, CMJ_{BSL3}) as the mean factor. The ANOVAs were performed for the following variables: height, leg stiffness, F_{peak}, ΔL, EH/RH ratio, and perceptive judgement scale.

In both experiments, post hoc analysis was performed using *t* test with Bonferroni correction. Statistical significance was set at $P \leq 0.05$.

Results

Main experiment

Measures of motor performance

The ANOVA showed a main effect of trial ($F = 2.82$, $P = 0.016$) and a significant surface * trial interaction ($F = 2.96$, $P = 0.013$) for leg stiffness (Fig. 2a). After repetitive jumps on the trampoline, leg stiffness increased significantly on CMJ_1 in comparison with CMJ_{bsl} ($P = 0.002$). Leg stiffness returned to baseline values by CMJ_2 (CMJ_{bsl} vs. CMJ_2: $P > 0.05$). Further evidence of the rapid return to baseline is supported by the observation that leg stiffness was also higher on CMJ_1 compared to the last four CMJs (CMJ_3 to CMJ_6: $P \leq 0.05$ for all comparisons). In contrast, adaptation on the rigid surface produced no changes in leg stiffness across the series of test jumps. Finally, in a comparison across surfaces, leg stiffness on CMJ_1 was greater following adaptation on the elastic surface compared to the rigid surface ($P = 0.039$).

Regarding the ΔL, the ANOVA showed a main effect of trial ($F = 3.192$, $P = 0.028$) and a significant surface * trial interaction ($F = 3.00$, $P = 0.012$; Fig. 2d). After repetitive jumps on the trampoline, ΔL measures decreased significantly on CMJ_1 and CMJ_2 in comparison with CMJ_{bsl} ($P \leq 0.05$) and returned to baseline values by CMJ_3 (CMJ_{bsl} vs. CMJ_3 to CMJ_6, $P > 0.05$). ΔL was also lower on CMJ_1 and CMJ_2 compared to the last four CMJs (CMJ_3 to CMJ_6: $P \leq 0.05$ for all comparisons). However, adaptation on the rigid surface produced no changes in the ΔL dynamics across the series of test jumps. Moreover, in a comparison across surfaces, ΔL on CMJ_1 and CMJ_2 was lower after the elastic surface compared to the rigid surface ($P = 0.010$ and $P = 0.049$ for CMJ_1 and CMJ_2, respectively). In relation to the peak force data, this parameter did not show any significant changes across the jumps and conditions (Fig. 2c).

Turning to jump height, the ANOVA showed a main effect of trial ($F = 10.78$, $P \leq 0.0001$) and a significant surface * trial interaction ($F = 2.42$, $P = 0.035$). Repetitive jumps on the trampoline led to a significant decrease in height on CMJ_1 in comparison with CMJ_{bsl} ($P = 0.005$, see Fig. 2b). Height increased over subsequent jumps, resulting in significant differences between CMJ_1 and CMJ_4 to CMJ_6 ($P \leq 0.05$ for all comparisons). CMJ_3 to CMJ_6 did not differ from CMJ_{bsl}. As with stiffness, adaptation on the rigid surface produced no changes in jump height. A comparison across the two adapting surfaces revealed that the height reached in CMJ_1 after jumping on the trampoline was significantly lower than that reached in CMJ_1 after repetitive jumps on the stiff surface ($P = 0.04$).

Measures of perceptual judgments

The analysis of ratio EH/RH showed a significant main effect for surface ($F = 17.62$, $P = 0.001$), trial ($F = 6.41$, $P = 0.01$), and a surface * trial interaction ($F = 7.21$ $P = 0.007$). Adaptation on the elastic surface led to a significant decrease of EH/RH (Fig. 2e). That is, the subjects underestimated how high they jumped. This effect was limited to the first jump ($P \leq 0.05$ for all paired comparisons). Thus, after the elastic surface, the subjects were jumping lower than before and they underestimated their jump height. For the stiff surface, there were no changes in EH/RH. The EH/RH ratio in CMJ_1 and CMJ_2 after jumping on the trampoline was significantly lower in comparison with repetitive jumps on the stiff surface ($P = 0.006$ and $P = 0.012$, respectively).

The analysis of the scores of the subjective ratings showed a significant main effect for surface ($F = 27.6$, $P \leq 0.0001$), trial ($F = 40.52$, $P \leq 0.0001$), and a surface * trial interaction ($F = 31.17$, $P \leq 0.0001$). Post hoc analysis revealed significantly larger scores for the elastic than for the stiff surfaces for CMJ_1, CMJ_2, and CMJ_3 trials ($P \leq 0.0001$, $P \leq 0.0001$, and $P \leq 0.05$, respectively). The altered perception of the jumps after the trampoline decreased significantly from CMJ_1 to the CMJ_4 trial (CMJ_1 vs. CMJ_2, $P \leq 0.0001$; CMJ_2 vs. CMJ_3, $P \leq 0.0001$; CMJ_3 vs. CMJ_4, $P \leq 0.01$). No differences were found between the last three trials (CMJ_4, CMJ_5, and CMJ_6; Fig. 2f).

Complementary experiment

The ANOVA showed a significant main effect of trial ($F = 8.96$, $P \leq 0.0001$) for leg stiffness (Fig. 3a). Leg stiffness increased on jumps performed after immediately each block of repetitive jumps on the trampoline in comparison with CMJ_{BSL1} ($P \leq 0.05$ for all paired comparisons). However, the leg stiffness for CMJ_{BSL1} was not different than the CMJ_{BSL2} and CMJ_{BSL3}, indicating that leg stiffness recovered quickly after the last block of jumps on the trampoline. Interestingly, we found significantly greater leg stiffness for the CMJ_{BK1} in comparison with CMJ_{BK4}, CMJ_{BK5}, CMJ_{BK6}, CMJ_{BK7}, and CMJ_{BK8} ($P \leq 0.05$ for all these comparisons). These results indicate that the effects of

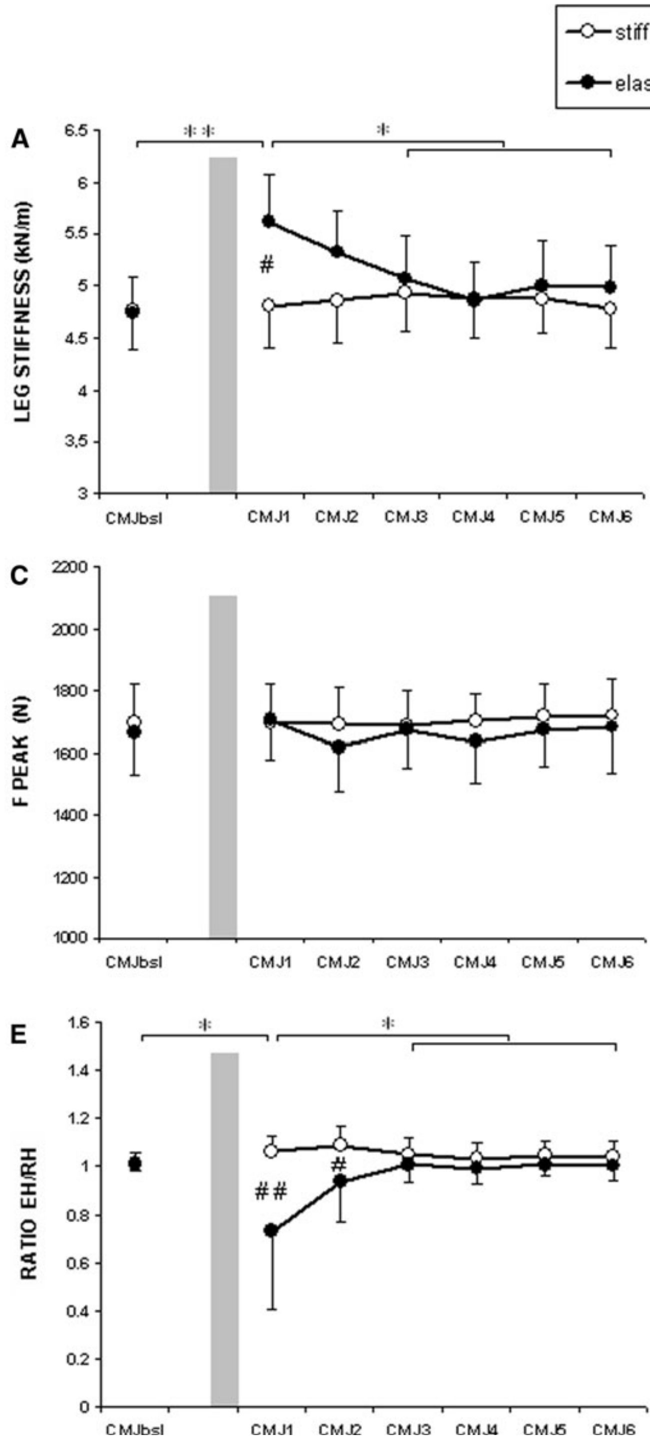

Fig. 2 Mean (±SEM) of leg stiffness (**a**), jump height (**b**), peak force (**c**), ΔL (**d**), ratio EH/RH (**e**), and perceptual scale scores (**f**) of CMJs before and after 1 min of repetitive jumps (*shaded square*) over stiff or elastic surfaces. (#) Differences between surfaces. (*) Differences between jumps on the elastic surface. Note that no changes were found between jumps on the rigid surface. (#), (*) $P \leq 0.05$; (##), (**) $P \leq 0.01$; (###), (***) $P \leq 0.001$

adaptation from trampoline jumping were reduced with successive inducing cycles of adaptation. Similar results were found for ΔL parameter. In this parameter, the ANOVA showed a significant main effect of trial ($F = 9.817$, $P \leq 0.0001$; Fig. 3d). ΔL decreased on jumps performed after each block of repetitive jumps on the trampoline in comparison with CMJ_{BSL1}, CMJ_{BSL2}, CMJ_{BSL3}, ($P \leq 0.05$ for all paired comparisons). There were no significant differences between CMJ_{BSL1}, CMJ_{BSL2}, and CMJ_{BSL3}, indicating a total recovery after the last block of

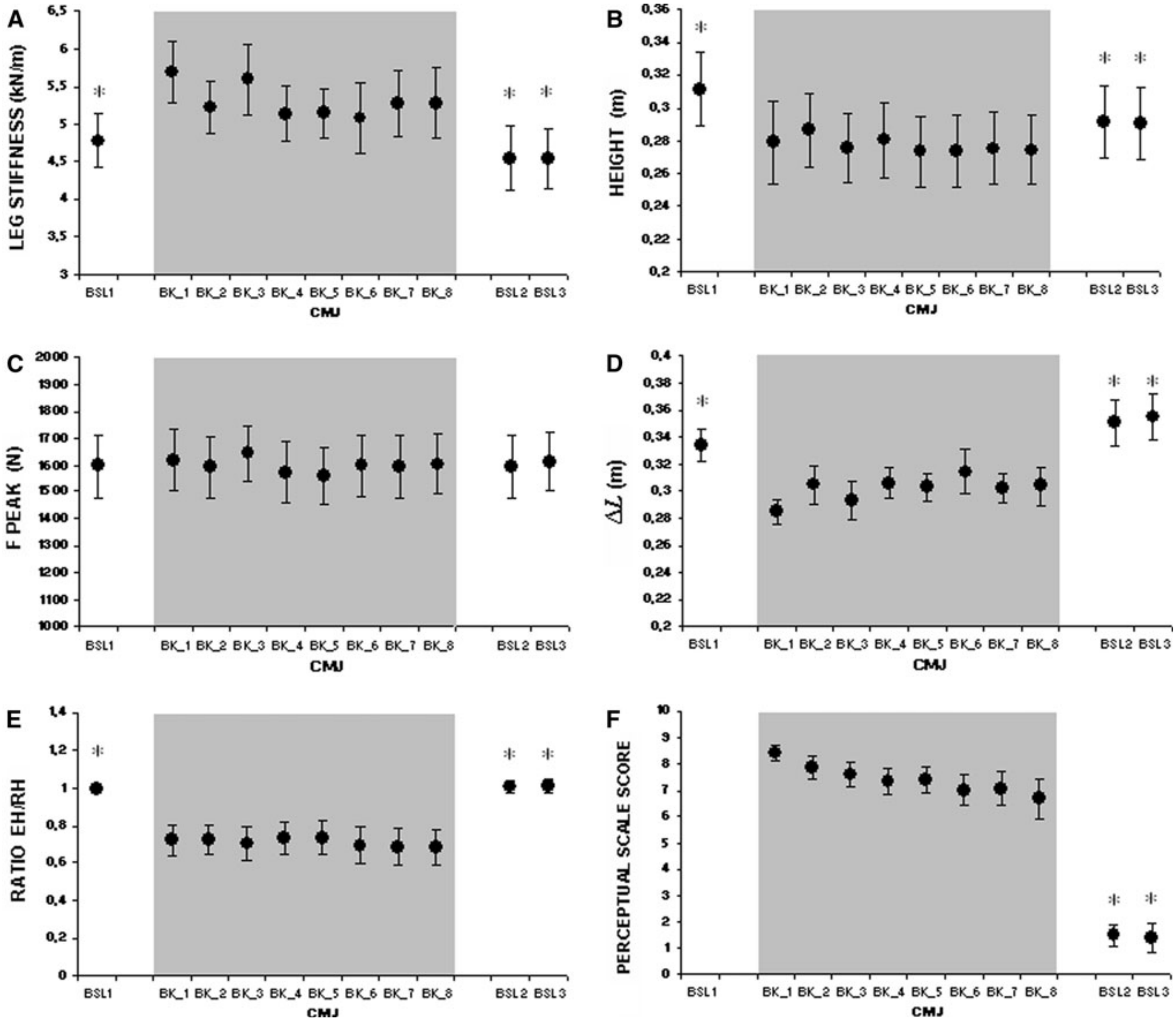

Fig. 3 Mean (±SEM) of leg stiffness (**a**), jump height (**b**), peak force (**c**), ΔL (**d**), ratio EH/RH (**e**), and perceptual scale scores (**f**) of CMJs before and after blocks of 1 min repetitive jumps (*shaded square*) over elastic surface. With exception of the peak force, the baseline values (CMJ_{BSL1}, CMJ_{BSL2}, CMJ_{BSL3}) were always significantly different to the CMJs performed immediately after the repetitive jumps (from CMJ_{BK1} to CMJ_{BK8}). Significant changes were found across CMJ_{BK} for leg stiffness and perceptual scale scores (statistic symbols not included in the figure), indicating a partial adaptation to the elastic surface. (*) indicates significant differences between CMJ_{BSL} and CMJ_{BK1}—CMJ_{BK8}

jumps on the trampoline. In addition, we did not find significant changes for ΔL dynamics across blocks. Regarding the peak force the ANOVA did not show any significant changes across trials (Fig. 3c).

The height of the jump showed a main effect of trial ($F = 7.42$; $P \leq 0.0001$; Fig. 3b). Jump height was reduced after each block of repetitive jumps in comparison with the CMJ_{BSL1} ($P \leq 0.05$ for all paired comparisons). No differences were found between the initial baseline and the final two jumps (CMJ_{BSL2} and CMJ_{BSL3}). Unlike the stiffness measure, we did not see a change in the modulation of jump height across successive adapting cycles.

The analysis of EH/RH ratio showed similar results to that of the jump height (Fig. 3e). There was a main effect of trial ($F = 10.00$, $P \leq 0.0001$) and the post hoc tests showed that the EH/RH ratio after each block of repetitive jumps was significantly lower than CMJ_{BSL1} ($P \leq 0.05$ for all paired comparisons). There were no differences between CMJ_{BSL1} and CMJ_{BSL2} and CMJ_{BSL3}, showing a total recovery of the EH/RH ratio after the initial post-adaptation jump following the last cycle. The underestimation of jump height persisted across the eight cycles of adaptation.

Regarding the subjective experience scores, there was a main effect of trial ($F = 45.66$, $P \leq 0.0001$). Significantly higher scores were observed for jumps after each block in comparison with the CMJ baseline ($P \leq 0.001$ for all paired comparisons). The score in the CMJ_{BK1} was significantly higher than that for CMJ_{BK6}, CMJ_{BK7}, and CMJ_{BK8} ($P = 0.013$, $P = 0.05$, and $P = 0.04$, respectively). These results indicate that subjects' impression of their jumps improved across the cycles (Fig. 3f).

Discussion

Following repetitive jumps on a trampoline, people exhibited increased leg stiffness and decreased jump height when asked to perform a single jump on a stiff surface (i.e. the ground). Moreover, these changes in motor performance were also associated with changes in the subjects' subjective experience of their performance.

It is important to emphasize that no previous studies have assessed sensorimotor aftereffects that involve a global body high-speed movement. Although we are aware of the difficulty of such an approach, we also believe that this study can contribute to a better understanding of how the current knowledge about sensorimotor adaptation applies to skills that are habitual in the field of sports.

The motor aftereffects

The increase of the leg stiffness during the first vertical jump after repetitive jumps on the trampoline was a consequence of the exposure to the elastic surface since there were no changes in the stiffness after repetitive jumps over the ground. Humans can adjust their musculoskeletal system to accommodate changes in surface stiffness, allowing them to maintain similar mechanics on different surfaces (Farley et al. 1998; Ferris and Farley 1997; Ferris et al. 1998; Moritz and Farley 2005). Most of these studies refer to rhythmic movements (hopping and running) rather than a discrete task such as the CMJ. Using the CMJ was important in this study for two main reasons. First, it allowed us to obtain an objective measurement of the motor performance. Second, the subjects were able to report the subjective perception of their performance for each jump. When we jump on an elastic surface, leg stiffness increases; the opposite is true for jumping on rigid surfaces (Ferris and Farley 1997). The current results show that the increased stiffness induced during trampoline jumping was maintained when the subjects first jumped on the rigid ground surface. This increased stiffness after the jumps on the elastic surface was the result of a decrease in the displacement of CoM, while the peak force remained unaffected. This modification of the displacement of CoM may be related to feedback from spindle muscles. However, recordings of neurophysiologic parameters need to be made in order to evaluate possible mechanism underlying the observed stiffness changes.

Our results are similar to the aftereffects observed in response to the Coriolis or inertial perturbation during movements of the arms (Lackner and DiZio 1994), legs (DiZio and Lackner 1997), and head (DiZio and Lackner 1995). These aftereffects are not context dependent since they occur when subjects carry over their adaptation from a rotating environment into a stationary one, indicating that the form of adaptation involves an internal model of the anticipated perturbation (DiZio and Lackner 2003). In line with this analogy, when subjects performed a new vertical jump over the ground after jumping on the elastic surface, an aftereffect was observed as a consequence of the erroneous predictions of the motor controller, resulting in a stiffer limb than was actually needed.

Several studies have focused on the influence of surface stiffness on leg stiffness during single events, such as a drop jump or landing from a jump (Moritz and Farley 2004; van der Krogt et al. 2009). These studies reported immediate changes in the leg stiffness during the landing on both expected and unexpected surfaces. This rapid change in leg stiffness (52 ms after the landing) may be due to a passive mechanism and not due to neural feedback (Moritz and Farley 2004). Passive adaptation may be critical when negotiating disturbances during locomotion across a variable terrain (van der Krogt et al. 2009). However, in our study, one trial was sufficient to recover the correct leg stiffness. Thus, a passive mechanism does not seem appropriate for accounting for our results.

One trial adaptation effects have also been observed for unexpected changes in surface friction (Johansson and Westling 1988) and object shape (Jenmalm and Johansson 1997). Reynolds and Bronstein (2003) showed a quick adaptation in the gait kinematics when subjects walked onto a stationary escalator. The recovery of the leg stiffness could be explained by a forward model of the forthcoming vertical jump (Bobbert et al. 2008). Such models can be trained and updated using prediction errors by comparing the predicted and actual outcome of a motor command (Wolpert and Flanagan 2001). Thus, the subjects could use the error between the predicted and actual sensory feedback occurred in the first CMJ after the trampoline, in order to update their internal model for the next jump.

After repetitive jumps on the trampoline, there was a decrease in the jump height in comparison with the previous jumps over the ground. This decrease in height could be a direct consequence of the change in leg stiffness (Bojsen-Møller et al. 2005; Farley et al. 1991; Liu et al. 2006). However, we cannot rule out other factors since jumping height is influenced by a combination of biomechanical, neural, metabolic, and morphological factors (Asmussen and Bonde-Petersen 1974; Bosco et al. 1982;

Kubo et al. 1999; Le Pellec and Maton 1999; Voigt et al. 1995).

Perceptive illusion

After repetitive jumps on the trampoline, the subjects reported a strong alteration in their subjective experience. When asked at the end of the experiment, to describe their subjective perception during the first post-adaptation jump, subjects usually reported very strong perceptions such as "I felt that I was not able to push my body upwards" or "I felt very heavy, as my legs suddenly increased their weight". Others' studies have described perceptive illusions in the field of gait and posture (Lackner and Graybiel 1981; Pelah and Barlow 1996; Hashiba 1998). Our results show that whole body fast movements (such as vertical jumps) can also result in strong perceptual illusions after a brief exposure to a new environment.

In addition to their qualitative impressions, the subjects also underestimated the actual height of their post-adaptation jumps. Note that this underestimation is relative to the actual height achieved. Thus, they not only achieve a lower maximum jump height, but their experience magnifies this reduction. Although the mechanisms underlying such perceptual illusions are not well understood, it has been proposed that they are produced by a sensory conflict between the visual, vestibular and somatosensory signals and the efference copy (Hashiba 1998). Jumps on the trampoline could lead to a new recalibration of sensory inputs due to continuous high acceleration of the body in the push-off phase of the jumps (around 0–4 g acceleration; Bhattacharya et al. 1980; Sovelius et al. 2008). This new recalibration between sensory modalities could disturb the relationship between self-induced motion and the expected sensory inputs when the subjects jump again on the ground. This could explain the erroneous estimation of the jump height reported by the subjects.

Lackner and Graybiel (1981) demonstrated an illusion of self-motion when subjects executed deep knee bends in the high force phase (2 g acceleration) of a parabolic flight. The subjects reported a perception of having moved downwards too rapidly and the support surface moving upwards under their feet. When they returned to 1 g acceleration level, subject experienced their movements as abnormal: the substrate of support and the visual world seemed unstable. The occurrence of such illusions could indicate that motor control is actively calibrated to a 1 g reference level. In the present study, subjects reported feeling the rigid surface stationary rather than moving upwards, after repetitive jumps on the trampoline. This suggests that departures from a 1 g reference level affect both the execution and appreciation of voluntary movement (Lackner and Graybiel 1981; Lackner and DiZio 2000).

Notably, in our study, repetitive jumps on the ground did not lead to perceptual distortions of subsequent, singular jumps on the ground. According to the sensory conflict hypothesis, this would be due to the fact that both repetitive and CMJ jumps were performed over the same surface and thus, there were no changes in the gravitational field that would require a new recalibration.

Persistence of the aftereffects

The second experiment explored how the motor and perceptive aftereffects were affected by repeated exposure to elastic-stiff surface transitions. The results show that continuous elastic-stiff surface transitions did not affect these aftereffects, although they slightly minimized the effects of the stiffness and subjective perception.

The decrease of the leg stiffness across the transitions suggests that, with experience, the sensorimotor system can adjust or anticipate the mechanical properties of different surfaces in an environment. However, leg stiffness continued to show some effects of each round of adaptation on the trampoline. The same trend was observed for the displacement of CoM while the peak force remained unaffected across the jumps. It is unclear if this effect would be totally abolished if we had increased the number of adaptation cycles.

In contrast to the leg stiffness, the height of the jump did not show any changes across successive cycles. As we mentioned above, the height of a jump is a variable affected by multiple factors. Thus, it is possible that the small adaptation in the leg stiffness may not be sufficient to revert the effect of the trampoline on the jump height.

We also observed a related dissociation between the two perceptual measures. Although the altered subjective perception produced by the first block of jumps on the trampoline did not disappear in the following blocks, it was progressively diminished. These results can be interpreted according to the sensory mismatch hypothesis (Wolpert et al. 1995; Blakemore et al. 1998). The subjective perception could arise due to an erroneous forward model where there is a mismatch between predictive and actual sensory feedback. In contrast, the subjects continued to underestimate their performance across the cycles. This result was surprising since we would expect a diminution in the estimation error to parallel with the trend observed for the subjective perception.

It may be subjective impressions and judgments of achieved height are different measures of sensory aftereffects. The former could be more closely linked to with the sensorimotor system and the latter with a cognitive/perceptual system. While the subjective perception provides information about the sensations experienced by the subject, the height estimation is the result of a cognitive process that translates perceptual and motor components of the movement into a self-performance measurement. In line with this idea, it has been shown that the sensoriomotor system can operate independently of the cognitive/perceptual system (Flanagan and Beltzner 2000), which could explain the difference in results obtained for the subjective perception and the error estimation.

In summary, the current results show that repetitive jumps on an elastic surface lead to motor and perceptual changes in subsequent jumps on a stiff surface. Adaptation on an elastic surface led to an increase in leg stiffness and a decrease in jump height. Moreover, the subjects underestimated their jump height and had the subjective impression that their jumps were performed more poorly than before adaptation. These changes were stables across the continuous surface transitions, since no changes were observed in the height estimation nor in the jump height. These after-effects likely reflect adjustments in an internal model from the elastic surface that carry over into movements produces on the stiff surface.

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