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ORIGINAL ARTICLE

Differential effects of countermovement magnitude and volitional effort on vertical jumping

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Abstract The importance of vertical jumping in sport and rehabilitative medicine is widely recognized. Despite the ample use of jump tests to assess neuromuscular function, the differential effects of muscular activation (volitional effort) and strategy (countermovement magnitude) on jumping performance have not been studied. The present study aimed to investigate the differential effects of countermovement magnitude and volitional effort on vertical jump performance. Ten male participants performed a total of 60 countermovement jumps each with three different countermovement knee angles (50, 70 and 90°) and four effort levels (25, 50, 75 and 100% of maximal effort). Kinematics and Kinetics were recorded using Vicon System together with a force platform. Electromyography of four muscles was recorded. Results show that countermovement magnitude and volitional effort both affect jump performance. These effects were synergistic for jump height ($P < 0.001$), but antagonistic for peak ground reaction force ($P < 0.001$). Interestingly, peak jump mechanical power was affected by volitional effort, implying an increase from 31.26 W/kg at 25% to 41.68 W/kg at 100% of volitional effort, but no countermovement magnitude effect was observed for 100% of volitional effort. This suggests that the apparent paradox of larger ground reaction forces in sub-maximal as compared to maximal jumps is due to the different jump strategies. Moreover, these results are relevant for jumping mechanography as a clinical tool, suggesting that peak power can be used to assess neuromuscular performance even when countermovement magnitude varies as a result of age or pathology.

Keywords Mechanography · Electromyography · Motor control · Jump strategy · Neuromuscular testing

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Introduction

Vertical jump capability is essential for many sports, and its assessment provides important insights into whole body power output in health and disease (Ferretti et al. 2001; Runge et al. 2004; Russo et al. 2003). In planning the specific features of a jump, the central nervous system (CNS) acts from a model of motor programs that exists for classes of movements to execute the task (van Zandwijk et al. 2000), anticipating the motor pattern required to achieve a specific jump height (Rittweger et al. 2007).

Jumps to a greater height require a larger countermovement and forward inclination of the trunk, and, when using the arm swing, they are associated with a greater height of the centre of mass (COM) at take-off (when ground reaction force = 0) than jumps with smaller height (Lees et al. 2006), the latter being referred to as 'submaximum' jumps in the literature (Lees et al. 2004; 2006; Vanrenterghem et al. 2004; van Zandwijk et al. 2000). In studies which used the arm swing, the greater height was associated with the increased height of the centre of mass at take-off, whereas a report using akimbo position (Vanrenterghem et al. 2004) compared submaximal and maximal vertical countermovement jumps (CMJ) and showed that different motor strategies are employed for the two jumps. According to their study, muscle power in such submaximal jumps is generated mainly from the calf muscles, whilst the mechanical energy for maximal jumps comes mostly from the thigh and hip musculature (Fukashiro and Komi 1987; Rodacki et al. 2002). That is, the calf muscles are the main contributor during submaximal jumps, when an 'ankle strategy' is adopted and the overall jump energy is comparatively small.

The performance in any jump is related to the impulse produced but it is interesting to note that, because of the duration of the contact phase is reduced considerably in submaximal jumps, to generate the required impulse there is a larger peak ground reaction force (GRF) applied. The fact that the peak GRF is larger in submaximal jumps may also be related to the velocity of contraction (slower in submaximal jumps) and the length of the triceps surae, since the calf muscles are primarily responsible for propulsion in these jumps as shown in the previous studies (e.g. Vanrenterghem et al. 2004). However, vertical jumps have, to the best of our knowledge, never been investigated with regards to combinations of different levels of muscle activation and countermovement magnitude.

It is important to fill this gap in the scientific literature for a number of reasons. Vertical jump tests, under the term 'jumping mechanography', have recently been introduced into the clinical test repertoire in paediatrics, in geriatrics, and in rehabilitative medicine (Rittweger et al. 2004). Jumping mechanography is a convenient test of neuro-muscular function that can be applied under clinical as well as under field conditions. Doing so, e.g., the decline in peak power with age has recently been shown to be a powerful estimator of biological age (Michaelis et al. 2008; Runge et al. 2004). Our own observations suggest, however, that the countermovement declines with ageing (Rittweger et al. unpublished data), but not after immobilisation by bed rest in young healthy people (Rittweger et al. 2007). It is well possible that countermovement magnitude, which is known to result in jump height (Lees et al. 2006) and to impact on peak GRF (Vanrenterghem et al. 2004) may also affect estimates of peak muscle power, which would lead to an underestimation of the age-related decline in muscle power as described by Runge et al. (2004).

Clearly, there is a need to assess the effect of countermovement magnitude on vertical jump performance, in terms of jump height, peak GRF and peak power, in order to provide the theoretical framework for the interpretation of clinical jumping mechanography. We, therefore, endeavoured to investigate the differential effects of countermovement magnitude and relative muscular activation levels on vertical jump performance. We hypothesized that, independently of the level of volitional effort (VE), the countermovement magnitude is inversely related to peak GRF and whole body peak jump mechanical power (PPeak), but directly related to jump height. As a secondary hypothesis of the study we expected PPeak and jump height to be directly related to VE for any given countermovement.

Materials and methods

The present study conforms to the Helsinki declaration and was approved by the local ethics committee (application no. ESS.2005.02.02). Informed consent was obtained from all participants before they were included into the study.

Study design

A study was designed in which participants were asked to perform countermovement jumps at four different VE levels and with three different angles of knee flexion during the countermovement prior to the jump. Ten male participants (age 26 ± 6 years; height 177.3 ± 3 cm; body mass 75.1 ± 5.5 kg) were recruited for this study through flyers or notices on the University campus. The experimental protocol consisted of two sessions scheduled 1 week apart. Firstly, the participants attended a 'familiarization session', which was dedicated to allow them to practice the generation of jumps in different knee flexion angles and different levels of VE at least twice. If necessary, a second session was performed for familiarization. The final session was then used for the data collection.

During data collection, participants were first asked to perform three maximal CMJ. The instruction was to 'jump as high as possible', disregarding any set flexion of the knee joint. Next, participants were asked to execute 60 CMJs, with all combinations of countermovement knee flexion (50°, 70° and 90°, where 0° corresponds to full extension) and VE (25, 50, 75 and 100% of maximal VE). Each of these 3 × 4 combinations was performed five times in a random order and a 60 s interval was allowed between jumps. The knee flexion and VE were controlled by, after each jump, asking the subjects whether they felt that the VE was as requested, and by checking the knee angle through Vicon Workstation software (see below). Whenever necessary (i.e. knee flexion and/or VE were not as requested), jumps were repeated immediately.

Data collection and processing

Kinematic data were collected using the Vicon Data Station 612 (Vicon Motion Systems, Oxford Metrics LTDA, Oxford, UK). Nine cameras operating at 120 frames per second were positioned surrounding a ground reaction force plate (Kistler Type 9865, Kistler Instrumente AG, Winterhur, Switzerland). Reflective markers were placed according to the Dempster's full body model for centre of mass position and values for segment mass and COM were used (Eames et al. 1999). An extra marker was placed on the great trochanter in order to serve as an accurate instant and quick feedback of the knee angle, in combination with the knee and ankle markers. All jumps were performed from the standing position with both feet on the force platform and the hands resting onto the waist (Fig. 1). Vertical components and the point of application of the GRF were sampled and recorded at 1,080 Hz.

Electromyography (EMG) signals of four muscles of one leg were recorded during the execution of the jumps (Bagnoli 16 EMG system, Boston, MA, USA), following the recommendations given by SENIAM (surface electromyography for the non-invasive assessment of muscles; Freriks et al. 1999). The EMG data were collected for a period of 10 s and at 1,000 Hz. The muscles selected were vastus lateralis, gastrocnemius lateralis, gluteus maximus and erector spinae longissimus. Using the EMGworks analysis software in its version 3.1.1.1 (Delsys Inc, Boston, MA, USA), the data were first rectified and then integrated over time. The push-off phase—period from when the COM is at its lowest point to when GRF is zero—was selected for the EMG analyses. Then, EMG amplitude time integrals were normalized to the 90°–100% condition for all jumps within each individual.

The vertical GRF values were normalized to body weight. PPeak was calculated as the peak jump mechanical power (in Watts) divided by body mass (in Kilograms). The data analysis for jump height, peak jump mechanical power and peak GRF as well as the time epoch graphs were conducted using Microsoft Office Excel (2003). Additionally, peak velocity, as a measure of impulse normalized to body mass, was obtained using Vicon Polygon software (version: 3.1; Vicon Motion Systems, Oxford Metrics LTDA, Oxford, UK) and squat time was calculated as the time between the start of the COM downward movement and the instance when the decreasing GRF reached zero.

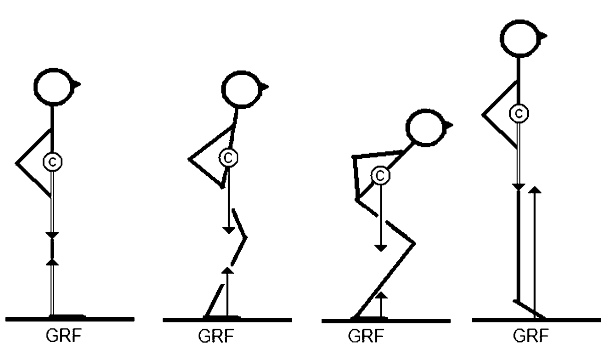

Fig. 1 Sequence of actions in a countermovement jump. The "C" is the representation of the centre of mass and the arrow is the line of action; whereas the "GRF" is the ground reaction force vector with its origin at the centre of the force platform. With a greater arrow, more force is exerted by the body on the ground

Statistical analysis

Data were analyzed with a two-way repeated measures analysis of variance (ANOVA) to test for significant effects of knee angle and VE level, and the interaction of the two. Bonferroni's test was used for post hoc analyses. The level of significance was chosen as $\alpha < 0.05$. Data are presented as mean ± SD. All statistical analyses were done with the Statistical Package for the Social Science (SPSS) software for Windows (Release 11.5.0, SPSS©, Inc., 2002).

Results

Out of the total of 600 jumps that were recorded (10 subjects × 60 jumps), seven could not be analyzed due to the data collection problems (markers were not detected or GRF was not recorded). Significant main effects of knee angle ($F_{2,92} = 219.2$, $P < 0.001$) and VE ($F_{3,138} = 178.3$, $P < 0.001$) were found on jump height, and there was also a significant interaction between knee angle and VE ($F_{6,276} = 7.3$, $P < 0.001$). Bonferroni post hoc analyses showed that jump height increased with the countermovement knee angle ($P < 0.001$ in all cases), and also with VE ($P < 0.001$ in all cases). Jump height was greatest for the 90°/100% VE condition (375 mm; see Fig. 2a).

The peak vertical GRF for the different knee angles and levels of VE is shown in Fig. 2b. ANOVA yielded a significant ($F_{2,80} = 367.7$, $P < 0.001$) effect for knee angle and VE ($F_{3,120} = 87.7$, $P < 0.001$). Moreover, a significant interaction between knee angle and effort was found ($F_{6,240} = 9.1$, $P = 0.004$). In contrast to PPeak (see below), peak vertical GRF was inversely related to knee angle. Bonferroni post hoc analyses revealed that the distinction in peak GRF is significant within knee angles (50, 70 and 90°) and levels of effort ($P < 0.001$ in all cases).

Analysis of PPeak (Fig. 2c) indicated a significant effect for knee angle ($F_{2,92} = 11.4$, $P < 0.001$) and VE ($F_{3,138} = 152.1$, $P < 0.001$), but no significant interaction between the two ($F_{6,276} = 1.7$, $P = 0.12$). Bonferroni post hoc analyses demonstrated that there were significant differences between the levels of effort ($P < 0.001$), and also when comparing knee angles of 50 and 70° ($P < 0.001$) and of 70 and 90° ($P = 0.003$), but, interestingly, not 50° in comparison with 90° ($P = 0.285$).

Figure 3A shows a typical example of GRF and height from the same subject performing jumps with 90° of knee

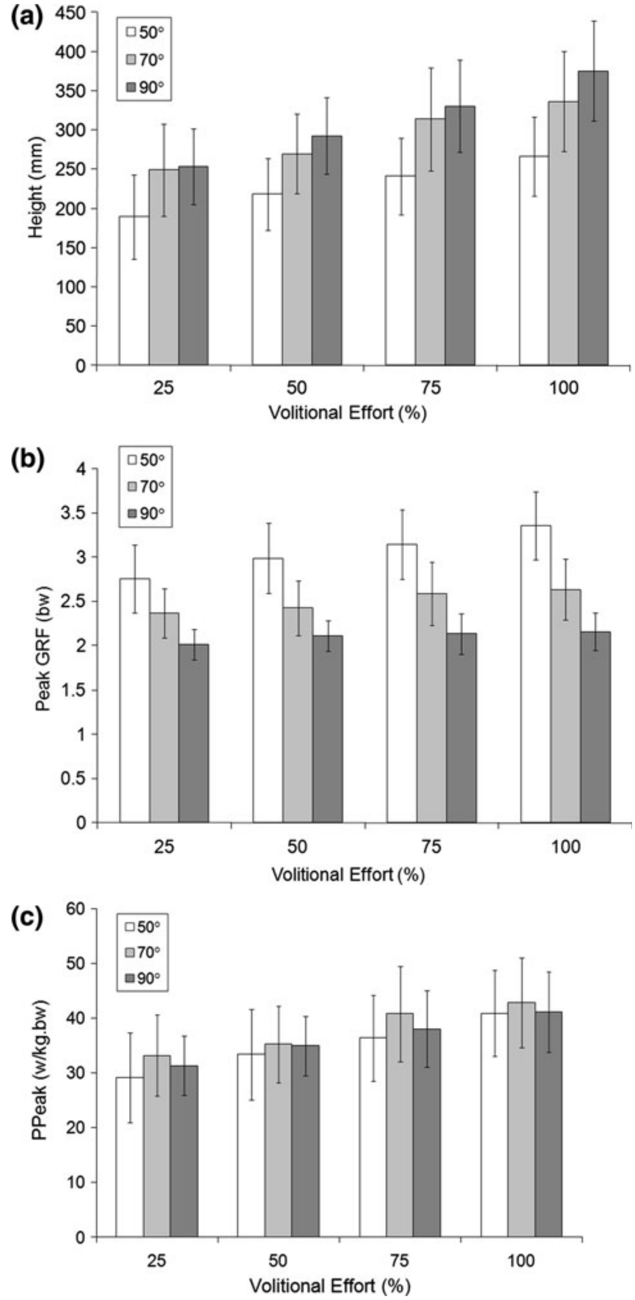

Fig. 2 **a** Mean ± SD of height in different knee angles before the jump, and with different levels of VE. Significant differences were found for both variables (knee angle and VE), and also for the interaction of both ($P = 0.001$ in all cases). **b** Mean ± SD for peak vertical GRF in different knee angles and VE. Difference is significant between both variables (knee angle and VE) and interaction ($P = 0.001$ in all cases). **c** Mean ± SD of PPeak in different angles of the knee and VE. Difference is significant between both variables (knee angle and VE) ($P < 0.01$ in all cases), but not significant for interaction ($P = 0.12$)

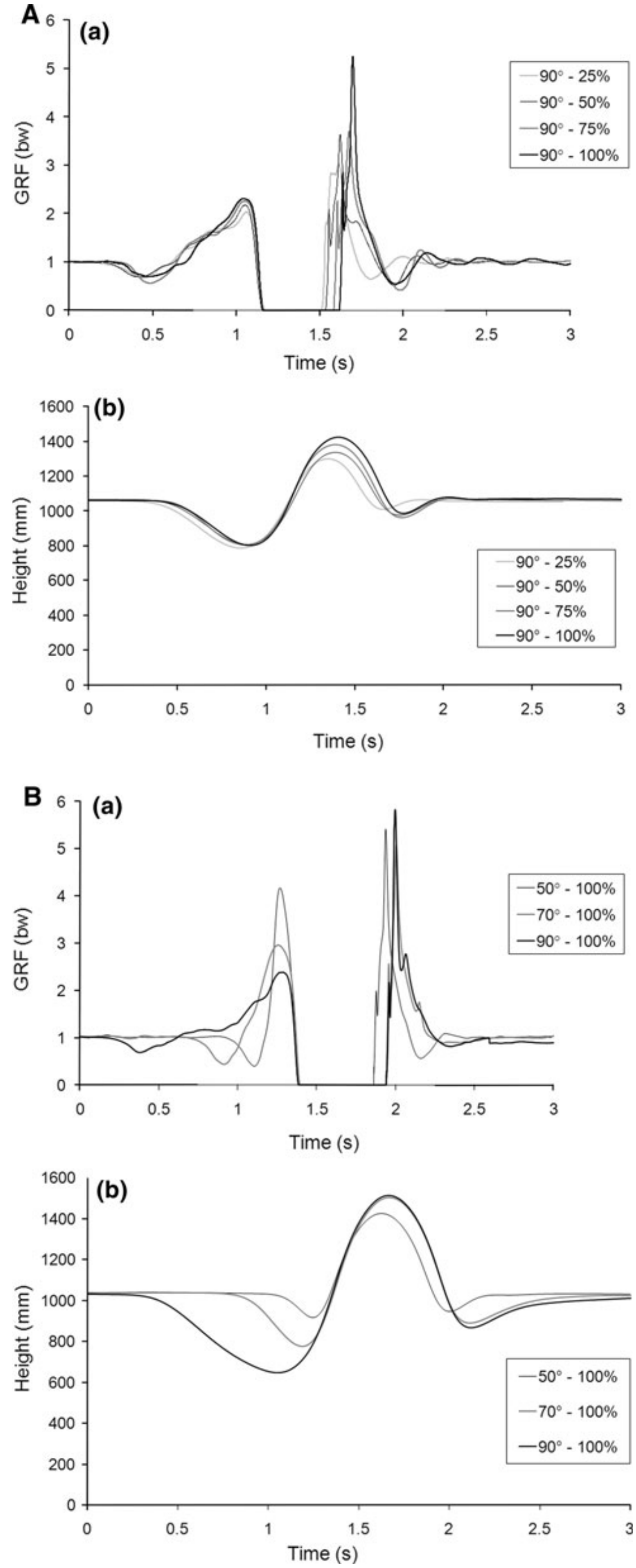

Fig. 3 **A** A typical example of GRF (*a*) and height (*b*) against time throughout four trials of 90° of knee angle in different levels of VE. These trials were all synchronized in time with regards to take-off. **B** A typical example of GRF (*a*) and height (*b*) against time throughout three trials in different knee angles at 100% of VE. These trials were all synchronized in time with regards to take-off

flexion in all levels of effort (25, 50, 75, 100%). As can be seen from the Figure, peak GRF and height increase approximately proportionally as the level of effort increases for a given knee angle (90° in this case). Figure 3B displays the changes in GRF and height in four trials performed by the same subject. In this case, height increases when the subject perform deeper countermovement jumps, whereas peak force decreases. Moreover, it can be seen that the greater knee flexion, the longer the squat (phase when the COM is going down) and push-off phase.

Analysis of peak torques from three distinct leg joints is shown in Fig. 4. Analysis of peak ankle torque indicated a significant knee angle ($F_{2,92} = 18.6$, $P < 0.001$), VE ($F_{3,138} = 208.2$, $P < 0.001$) and interaction between them ($F_{6,276} = 5.5$, $P < 0.001$). Post hoc test showed significant differences between levels of effort ($P < 0.001$) and knee angles ($P < 0.05$) with the exception of the 70 and 90º compared ($P = 0.58$). The ANOVA for peak knee torque showed a significant effect for knee angle ($F_{2,92} = 68.5$, $P < 0.001$), VE ($F_{3,138} = 80.2$, $P < 0.001$) and for the knee * effort interaction ($F_{6,276} = 2.5$, $P < 0.05$). Bonferroni's post hoc test indicated significant differences between all levels of effort ($P < 0.05$) and knee angles ($P < 0.001$). Analysis of peak hip torque demonstrated a significant difference for knee angles ($F_{2,92} = 80.8$, $P < 0.001$) and VE ($F_{3,138} = 41.3$, $P < 0.001$), but not for the interaction ($F_{6,276} = 1.6$, $P = 0.16$). Post hoc indicated significant differences between knee angles ($P < 0.001$ in all cases) and for 100% of VE in comparison with all other VE ($P < 0.001$ for all) and 25 compared to 75% ($P < 0.001$), but not for 50% in comparison to 25 and 75 condition ($P = 0.15$ and $P = 0.27$, respectively).

EMG analysis indicated significant differences ($P < 0.05$ for all muscles analyzed) between knee angles (Fig. 5a). Furthermore, non-significant differences for neither VE ($P > 0.05$ for all muscles analyzed except vastus lateralis

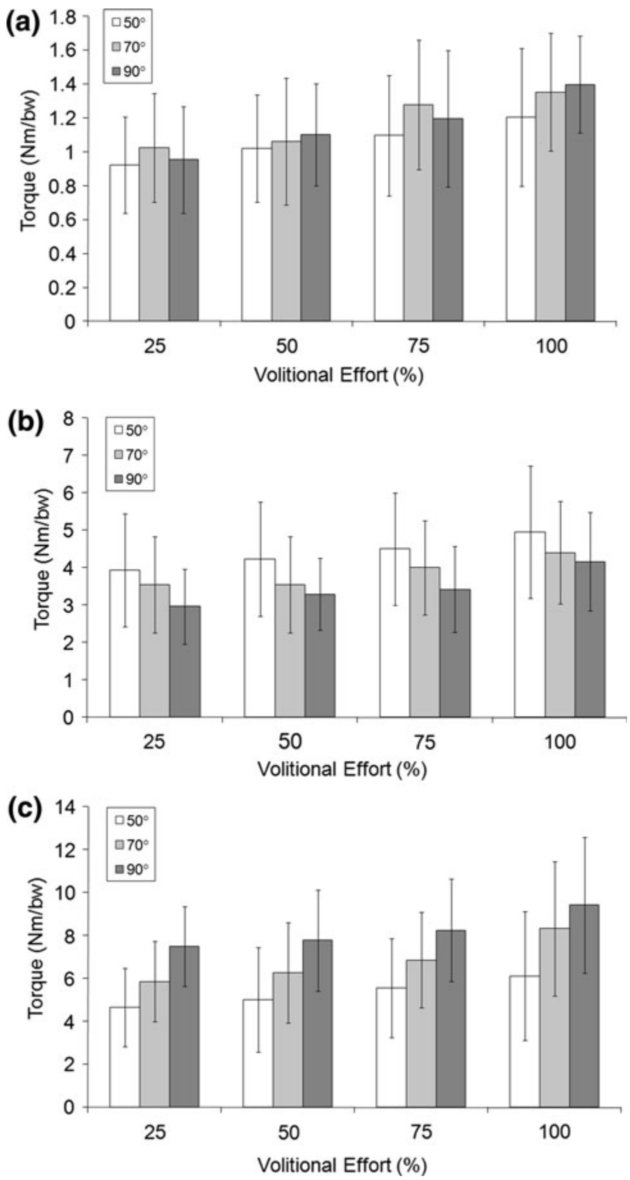

Fig. 4 **a** Mean ± SD of peak ankle torque in different knee angles and levels VE. Significant differences were found for both variables and also for their interaction ($P < 0.05$ in all cases). **b** Mean ± SD of peak knee torque in different knee angles and levels VE. Significant differences were found for both variables and also for their interaction ($P < 0.05$ in all cases). **c** Mean ± SD of peak hip torque in different knee angles and levels VE. Significant differences were found for knee angles ($P = 0.00$) and VE ($P < 0.05$) but not for their interaction ($P > 0.05$)

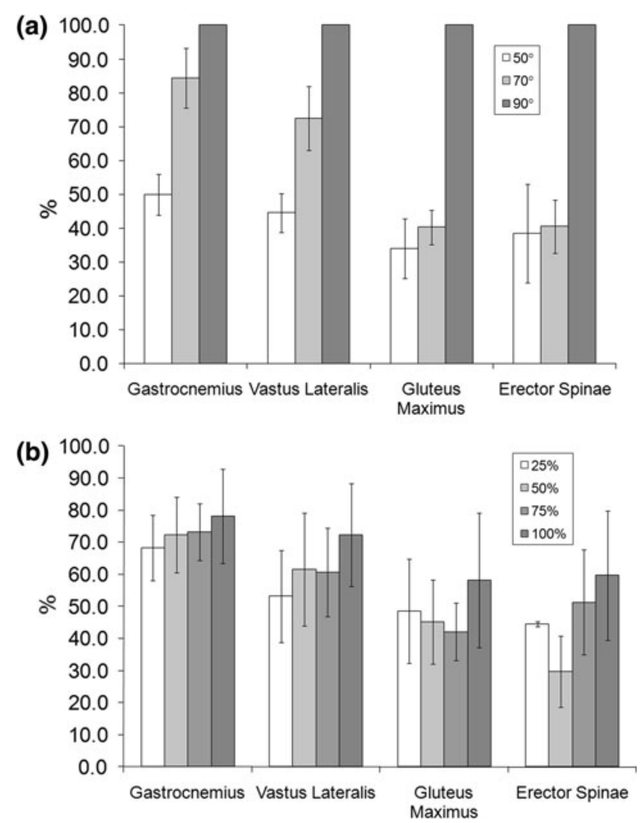

Fig. 5 **a** Mean ± SD of integrated EMGs of four muscles in push-off phase in different knee angles at 100% of VE. **b** Integrated EMGs of four muscles in push-off phase in various VE. Data presented as mean ± SD of 25, 50, 75 and 100% of VE

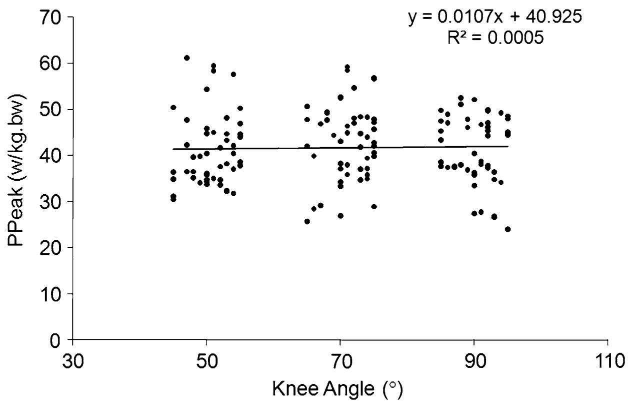

Fig. 6 PPeak and knee angle at 100% of VE

which was found significant) nor interaction ($P > 0.05$ for all muscles analyzed) was found (Fig. 5b).

Importantly, no effect on PPeak was found by knee angle in the 100% VE condition ($P = 0.49$; Fig. 6).

In the present study, neither hip nor ankle angles were controlled. However, further statistical analysis of peak hip flexion and peak ankle dorsiflexion was carried out to explore the contribution of the hip and ankle angles in relation to knee angle and VE. As expected, ANOVA analysis revealed that hip flexion increased significantly in greater knee angles and VE ($P < 0.001$), but not for interaction ($P > 0.05$). That is, the greater the knee angle, the greater hip flexion. In addition, post hoc analysis indicated that VE was only significant when comparing 100% with 25 and 75%. Besides, the interaction between knee angle and VE was non-significant ($P > 0.05$). On the other hand, ankle dorsiflexion was solely a reflection of the knee ankle (i.e. greater knee angle, greater ankle dorsiflexion), since significant differences were found for knee angle ($P < 0.05$), but not for VE ($P > 0.05$). Figure 7 shows a comparison of the peak values for hip and ankle angles.

In addition, peak vertical velocity and the squat time (i.e. time from when the COM starts to go down to when GRF is equal to zero) were also analyzed as to detect any significant differences in the jumping strategy. ANOVA analysis of the peak velocity failed to show any significant effect of knee angle or VE ($P > 0.05$; Fig. 8), whereas squat time yielded a significant knee effect ($P < 0.05$; Fig. 9), but not VE effect ($P > 0.05$).

Discussion

The main purpose of this study was to elucidate to what extent CMJ with a pre-defined knee angle and VE affects jumping performance. It is important to point that muscular activation is likely to be the major factor behind the VE effect, but other elements may be involved as well, such as

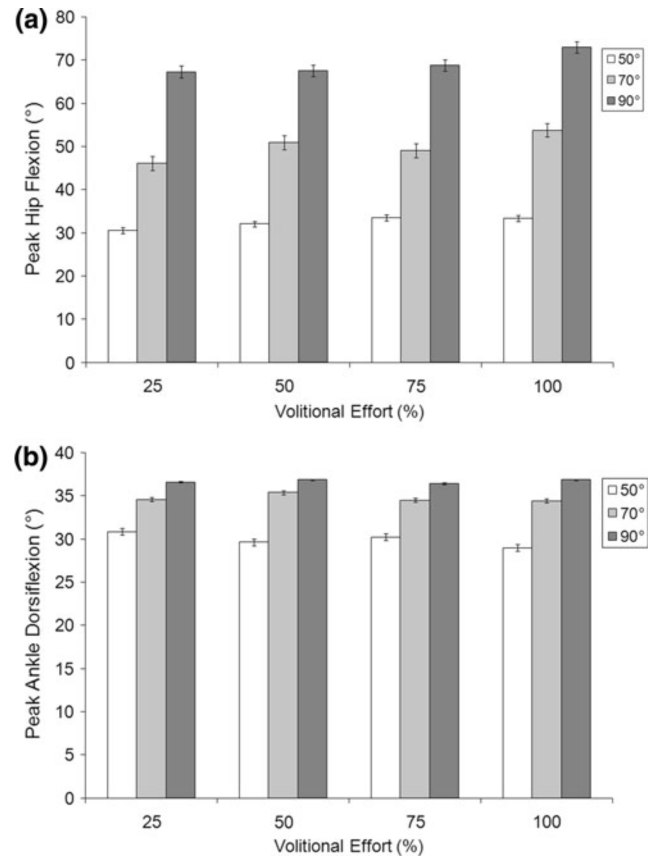

Fig. 7 **a** Mean ± SD of peak hip flexion in different knee angles and levels VE. With greater angle, the greater hip flexion. Significant differences were found for both knee ankle and VE, but not for their interaction ($P < 0.05$ in all cases) **b**. Mean ± SD of peak ankle dorsiflexion in different knee angles and levels VE. With greater angle, the greater ankle dorsiflexion

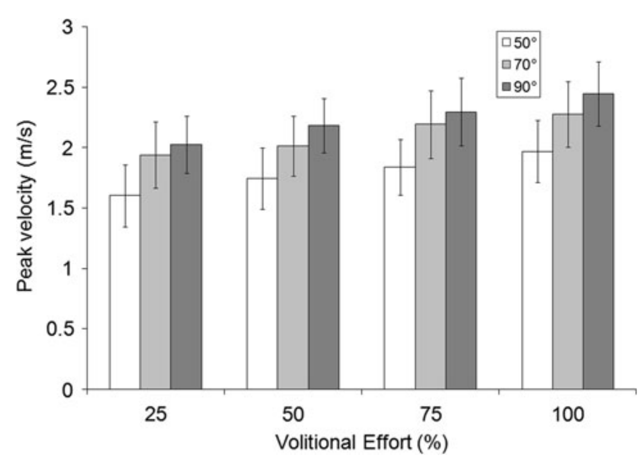

Fig. 8 Mean ± SD of peak vertical velocity in different knee angles and levels VE. AVOVA analysis did not show any significance for neither knee ankle nor VE ($P > 0.05$ in both cases)

intra and inter muscular co-ordination. The results showed that countermovement magnitude positively affects jump height and peak joint (ankle, knee and hip) torques, is

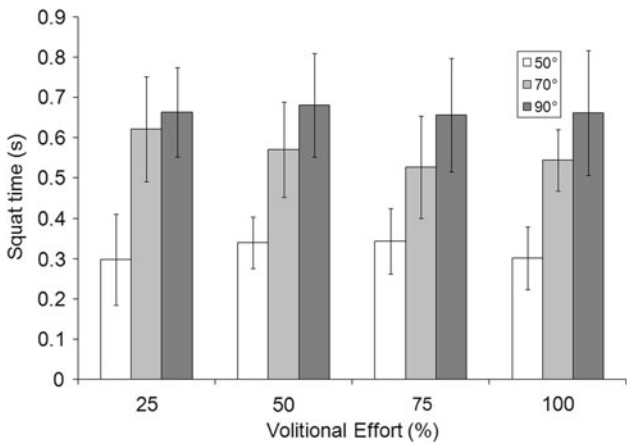

Fig. 9 Mean ± SD of squat time in different knee angles and levels VE. Significant differences were found for knee angle ($P < 0.05$), but not for VE ($P > 0.05$)

negatively related to peak GRF, but has very little or no bearing on peak power. Conversely, volitional effort is positively related to all four of these factors of jumping performance.

These results have a number of implications. Firstly, they confirm the notion that the seeming paradoxon referred to above (i.e. smaller peak vertical ground reaction forces in higher jumps) is largely due to the different motor strategies and biomechanical configurations, thus confirming the explanation proposed by Vanrenterghem et al. (2004). As reported in the literature, comparatively high GRF values can be generated by the use of only the ankle plantar flexors in a vertical jump (Dowling and Vamos 1993; Fukashiro and Komi 1987; Zajac et al. 1984). Furthermore, the movement to execute a jump from 90° knee angle (maximal jumps) depends mainly on the contribution of the energy generated by the hip and knee bi-articular muscles (e.g. quadriceps and hamstrings), whereas the movement from 50° (submaximal jumps) depends primarily on the ankle plantar flexors—a negligible muscle activity from hip is found (Fukashiro and Komi 1987; Vanrenterghem et al. 2004). In addition, Vanrenterghem et al. (2004) reported that when jumping 25% of the maximum jump height, 78% of the work is done in the distal ankle joints, whereas jumping at 100%, only 23% is the contribution from the ankle. Peak GRF (Fig. 3B) at the end of the propulsion period is related to the fact that at that point the knee and hips are already extended and, therefore, the only joint that can contribute further is the ankle because it is not fully plantarflexed yet. This is consistent with the proximal-to-distal sequence of activation as well. Although the calf muscles are limited and increasing jump heights require an increased knee and hip contribution, the high peak vertical forces can be achieved only by activity from the calf muscles during that stage of the propulsion.

Our EMG results, as well as the timing of the countermovement support this interpretation. Regardless of the muscle analyzed, the countermovement magnitude was positively related with the level of neuromuscular excitation (Fig. 5a). The increase in EMG values for gluteus maximus and erector spinae was in accordance with the greater countermovement magnitude (knee angle) and also to greater hip and ankle torque (Fig. 4a, c). According to Lees et al. (2004) greater knee angle during the countermovement causes a larger forward inclination of the trunk and consequently requires an increased torque and power from the hip muscles. Furthermore, the greater the countermovement, the greater will be the impulse, the muscular activation (especially from bi-articular muscles) and consequently the jump height. Paradoxically, as shown in Fig. 4b, peak knee torque deceased with countermovement depth. This may be due to the flexion of the hip, which implies greater hamstrings activation. Greater hamstrings activation apparently leads to a lower knee torque (van Zandwijk et al. 2000).

Our results have also some quite practical implications. Peak jump mechanical power, which is increasingly used as an endpoint in physiological and epidemiological studies (Pearson et al. 2002; Rittweger et al. 2007; Runge et al. 2004), was not affected by the countermovement magnitude (Fig. 6). This means that different strategies of countermovement do affect peak height and force but not power. This is an important observation under conditions, where the countermovement may vary during the course of a study or between different study groups. In essence, our data suggest that peak height, peak force and peak torque are all affected by variation in countermovement magnitude, whilst peak power appears to be comparatively robust.

As a limitation of our study, one has to consider that voluntary effort is subjective. However, VE did translate into reproducible and meaningful variation of jump height (Fig. 2a), peak power (Fig. 2c), and not least to different levels (i.e. percentages) of neuromuscular activation, as evidenced by our EMG analyses (Fig. 5b). Apparently, the most usual and easy to reproduce VE is the maximum (100%), probably because the CNS exerts a fixated control to allow for maximal performance. Therefore, subjects are able to learn and develop maximal efforts during their lives. On the other hand, individuals can train submaximal jumps but do not usually train sets of submaximal performances (e.g. exactly 70% of effort). Although the participants were asked after every jump if that effort was the same as requested by the investigator, this indirect judgment and the lack of submaximal performances training can lead to inaccuracies in the results. However, considering that the results were consistent, we do not believe these inaccuracies were significant to invalidate the current protocol.

Conclusions

In conclusion, our study has shown that both VE and countermovement magnitude affect jump performance. Their effect on jump height, peak torque and neuromuscular activation is synergistic (i.e. in the same direction), but the two factors have opposing effects on peak vertical ground reaction forces. Interestingly, peak jump mechanical power was affected by the VE only, and not by countermovement magnitude.

These results suggest that peak power in vertical jumps may be a descriptor of neuromuscular function that is robust against variation in jumping strategy.

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Conflict of interest The authors declare that they have no conflict of interest.

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