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Control Strategy of Maximum Vertical Jumps: the Preferred Countermovement Depth May Not Be Fully Optimized for Jump Height

by

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The aim of the present study was to explore the control strategy of maximum countermovement jumps regarding the preferred countermovement depth preceding the concentric jump phase. Elite basketball players and physically active non-athletes were tested on the jumps performed with and without an arm swing, while the countermovement depth was varied within the interval of almost ±30 cm around its preferred value. The results consistently revealed 5.1-11.2 cm smaller countermovement depth than the optimum one, but the same difference was more prominent in non-athletes. In addition, although the same differences revealed a marked effect on the recorded force and power output, they reduced jump height for only 0.1-1.2 cm. Therefore, the studied control strategy may not be based solely on the countermovement depth that maximizes jump height. In addition, the comparison of the two groups does not support the concept of a dual-task strategy based on the trade-off between maximizing jump height and minimizing the jumping quickness that should be more prominent in the athletes that routinely need to jump quickly. Further research could explore whether the observed phenomenon is based on other optimization principles, such as the minimization of effort and energy expenditure. Nevertheless, future routine testing procedures should take into account that the control strategy of maximum countermovement jumps is not fully based on maximizing the jump height, while the countermovement depth markedly confound the relationship between the jump height and the assessed force and power output of leg muscles.

***Key words**: dual-task; trade-of; optimum; quickness; force; power.*

Introduction

Maximum vertical jumps have been extensively used in different areas of human movement science for various purposes, such as training and testing of leg muscles (Hori et al., 2007; Markovic et al., 2004, 2013), as well as for studying the basic mechanical properties and mechanisms of the neuro-muscular system associated with production of maximum movement performance (Bobbert, 2014; Jaric and Markovic, 2009, 2013; McMahon, 1984). When used in routine testing, the typical instruction given is to jump as high as possible in a natural fashion with a preceding countermovement (i.e., the countermovement jump; CMJ). The most frequently obtained variable has been the maximum jump height (Hjump) that directly represents the task performance. However, Hjump has also been indiscriminately interpreted as an index of force, velocity or power-producing properties of leg muscles (Jaric, 2015, 2016). Therefore, the implicit presumption behind such interpretations has been that Hjump is not only

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strongly related with the maximum movement velocity, but also positively related with the maximum force and power output of leg muscles (Cormie et al., 2011; Markovic and Jaric, 2007a; Samozino et al., 2013).

Recent studies, however, have revealed several problems related with the CMJ kinematic patterns and its effects on other frequently obtained mechanical variables. One problem could be the typical implicit presumption that the experienced subjects are able to select an optimum countermovement depth (Hcmd) to maximize Hjump. However, Hcmd is known to vary over a series of consecutive trials (Markovic et al., 2013) and may also be affected by training procedures (Hunter and Marshall, 2002; Markovic et al., 2013) or changes in external loads (Markovic et al., 2011). Several recent studies have revealed confounding effects of Hcmd not only on Hjump, but also on the recorded force and power output (Bobbert et al., 2008; Markovic et al., 2014; Samozino et al., 2012). Namely, while a 'deeper countermovement' (i.e., larger Hcmd) markedly reduces the recorded force and power output, its effect on Hjump is relatively small (Bobbert et al., 2008; Domire and Challis, 2007). As a result, the assessment of the force- and power-producing capacities of leg muscles from the recorded Hjump should be questioned.

An even more important problem could not be related to the Hcmd variability, but also to the preferred magnitude of Hcmd per se. Namely, our recent study showed that elite basketball players systematically selected Hcmd that was well below its optimum value for maximizing Hjump (Mandic et al., 2015). We interpreted the finding as a consequence of the vertical jumping being a dual task for such athletes. Namely, both in basketball and a number of other sport games the success depends not only on the jump height, but also on the jumping quickness. As a result, the elite players could have developed a jumping technique characterized by a somewhat smaller preferred Hcmd that trades a small part of Hjump for being able to perform a quicker jump (Mandic et al., 2015). However, the same reduction resulted in a prominent decrease in both the force and power output. Therefore, a question remains whether the preferred Hcmd well below the optimum one is typical only for selected groups of competitive athletes or, alternatively, it can be generalized across other populations. If the later were true, the mechanisms underlying such a phenomenon would deserve attention, while both the methods for testing the CMJ and the interpretation of obtained results would need to be revisited.

To address the problems presented above, we designed a study to investigate the preferred Hcmd of the maximum vertical jumps performed by both elite athletes and physically active non-athletes. The main aim of the present study was to explore the preferred Hcmd of maximum vertical jumps in relation to the optimum Hcmd that maximized Hjump. We specifically hypothesized that (H1) the preferred Hcmd would be smaller than the optimum one, as well as that (H2) the same difference would be more pronounced in the basketball players who regularly performed vertical jumps that needed to be both high and quick. Our secondary aim was to assess the effect of Hcmd on jumping mechanics. In line with previous studies, we expected a prominent negative relationship between Hcmd and both the force and power output, while the same effect on Hjump would be relatively weak. The expected results could be of importance for understanding the control of Hcmd in vertical jumping and, consequently, the control of the reversal phase of other cyclic movements, as well as for interpretation of the outcomes of various training and testing procedures based on vertical jumping.

Material and Methods

Participants

Eleven elite basketball players (I National league level; age 21.8 ± 2.9 years; body mass 87.3 ± 7.7 kg; body height 193.5 ± 5.7 cm) and 11 male physically active subjects (physical education students; age 22.6 ± 0.9 years; body mass 76.8 ± 10.7 kg; body height 182.5 ± 7.5 cm) were recruited for the study. Since body size could have prominent scaling effects on the jumping patterns (Jaric, 2003; McMahon, 1984), only the participants who were not taller than 2 m were included in the study. None of the participants reported recent injuries or chronic diseases that could compromise the tested performance. The study was conducted in accordance with the Declaration of Helsinki and all participants signed informed consent approved by the Review Board of the Faculty of Sports and Physical Education, University of Belgrade.

Procedures

The experimental procedure applied to both subject groups was carried out through the familiarization and experimental session separated by at least three days of rest. Prior to both sessions, each participant was given a 5 min warm-up period on a stationary bicycle, followed by 5 min of active and passive stretching exercises and 2 sets of 5 submaximal jumps. Thereafter, each participant performed a block of 20–23 maximum countermovement jumps either without (CMJ) or with a natural arm swing (CMJA; see further text for detailed explanations). The countermovement depth (H_{cmd}) of both jump types was manipulated with respect to the initially self-determined preferred H_{cmd}. Specifically the jumps were performed with a small, preferred and large H_{cmd}. Both the order of jump types and the order of selected H_{cmd} were randomized. The participants were instructed to avoid any strenuous exercise over the course of the experiment.

Prior to the blocks of trials for each jump type (i.e., CMJ and CMJA), each participant performed a block of 5 maximal jumps that served only for establishing the preferred H_{cmd}. Thereafter, participants performed 3 blocks of maximum jumps in a random sequence that served for data collection. Specifically, they performed 5 jumps from the preferred H_{cmd}, 5 jumps from the small and 5 jumps from the large H_{cmd} (see Mandic et al. (2015) for a similar procedure). For the 2 blocks of preferred H_{cmd}, subjects were solely instructed to jump as high as possible. Regarding the blocks performed from the small and large H_{cmd}, participants were instructed to jump as high as possible either "by going less deep" or "by going deeper into the squat", respectively. In both blocks, H_{cmd} was targeted to be between 10 and 20 cm different from the initially assessed preferred H_{cmd}. In case that individual trial revealed H_{cmd} out of the target interval (i.e., ±30 cm with respect to the preferred H_{cmd}), it was discarded and the participant was instructed to repeat the trial. However, the instruction regarding the maximization of jump height was always reiterated.

Measures

All jumps were performed on a force plate (AMTI BP600400; USA), mounted and calibrated according to the manufacturer's specifications (Figure 1A). Data acquisition and processing was completed using the custom-designed software (LabVIEW, National Instruments, Version 13.0, Austin, TX, USA). The vertical component of the ground reaction force (F) was recorded at a sampling frequency of 1000 Hz. The change in the vertical position of the subject's center of mass was calculated by consecutive integrations of the acceleration signal obtained from F. Each individual set of data was immediately checked for integration drift and correction was made when needed. In addition to the maximum displacement of the center of mass during the eccentric (i.e., the countermovement depth; H_{cmd}) and flight (jump height; H_{jump}) phase of the jump, we also recorded the duration of the concentric jump phase (T_{con}), the maximum F (F_{max}) and calculated P as the maximum power (P_{max}) from the concentric jump phase as the maximum product of F and the velocity of the center of mass. Note that the kinematic and kinetic variables observed from maximum vertical jumps proved to be highly reliable (Markovic et al., 2004), even including H_{cmd} (Moir et al., 2009).

Statistical Analysis

Descriptive statistics were calculated for all experimental data as mean and standard deviation (SD) values. Due to the observed data patterns, the effect of H_{cmd} on H_{jump} and F_{max} was assessed by the second-order polynomial, while the same effect on T_{con} and P_{max} was assessed by the linear regression model (see Mandic et al. (2015) for a similar approach). The maxima of polynomial regression models were used to assess the optimum H_{cmd} for maximizing H_{jump}. Paired t-tests were used to separately evaluate the differences between the preferred and optimum H_{cmd}, both in 2 groups and 2 jump types. Two-way mixed-design ANOVA (factors "group" and "countermovement depth") was applied to assess potential differences between the preferred and optimum H_{cmd} between athletes and physically active participants. Partial eta-squared ($_p\eta^2$) was employed to assess the corresponding effect sizes. Where significant main effects of factors or their interaction were found, the Bonferroni post-hoc test was applied. Alpha was set at 0.05. Data were analyzed using SPSS 20.0 software (SPSS Inc. Chicago, IL, USA).

Results

Figure 1 depicts typical time series of the dependent variables obtained from a representative athlete when performing the jumps from the small, preferred and large countermovement depth (H_{cmd}). Note that the jump height (H_{jump}) is slightly higher for the preferred than for either the small or large H_{cmd}. However, both the maximum ground reaction force (F_{max}) and the maximal power (P_{max}) gradually decrease with an increase in H_{cmd}.

Preferred and optimum countermovement depth

The optimum H_{cmd} was determined from the relationship between H_{cmd} and H_{jump} obtained from the second-order polynomial regression model applied on the sets of the data obtained by all subjects of the 2 groups (Figure 2). The model revealed a strong relationship for both the athletes (r = 0.86 and r = 0.66) and the physically active participants (r = 0.88 and r = 0.81; for CMJ and CMJA, respectively), while the preferred H_{cmd} was consistently smaller than the optimum H_{cmd} that maximized H_{jump}. However, of potential importance here could also be that the fitted polynomial regression models were relatively flat. As a result, the athletes on average lost only about 0.7 and 0.1 cm of their H_{jump} due to the preferred H_{cmd} being 8.6 and 5.1 cm smaller than the optimum one in the CMJ and CMJA, respectively. Preferred H_{cmd} of physically active participants was 11.2 and 7.1 cm smaller than the optimum H_{cmd} resulting in the loss of on average 1.2 and 0.8 cm of their H_{jump}.

While Figure 2 shows the relationship between H_{jump} and H_{cmd} and the differences between the preferred and optimum H_{cmd} obtained from the data of all subjects pulled together, the same analysis was separately conducted on individual sets of the data. In general, the individual relationships between H_{jump} and H_{cmd} proved to be exceptionally strong. Specifically, the correlation coefficients were r = 0.91 (0.85 - 0.97) and r = 0.94 (0.89–0.98) for CMJ and r = 0.87 (0.59 - 0.94) and r = 0.90 (0.66–0.96) for CMJA for the athletes and physically active individuals, respectively (data presented as medians with ranges). The averaged across the subject values of the preferred and optimum H_{cmd} shown in Figure 3 proved to be similar to the same values observed from the pooled data and depicted in Figure 2. The individual differences between the preferred and optimum H_{cmd} proved to be significant in both groups and both jump types (all p < 0.01; paired t-test). However, of particular importance here are the *differences* between the preferred and optimum H_{cmd} also shown in Figure 3. Two-way mixed model ANOVA revealed the main effects of the jump type ($F_{1,108}$ = 118.3; p < 0.001; ${}_p\eta^2$ = 0.523) and group ($F_{1,108}$ = 13.2; p < 0.05; ${}_p\eta^2$ = 0.14), but not their interaction ($F_{1,108}$ = 0.8; p > 0.05; ${}_p\eta^2$ = 0.008). Specifically, the difference between the preferred and optimum H_{cmd} was larger in the CMJ than in the CMJA. However, of utmost importance here is that the same differences were larger in the physically active individuals compared to athletes.

Effects of countermovement depth on duration of the concentric jump phase

Similar to the effect of H_{cmd} on H_{jump} (Figure 2), Figure 4 shows the effect of H_{cmd} on the duration of the concentric jump phase (T_{con}). The linear regression model shows exceptionally strong positive relationships between the 2 variables in both groups and jump types (0.98 < r < 0.99). Of particular importance is that the preferred H_{cmd} smaller than optimum one resulted in a shorter T_{con} (0.054 and 0.028 s in athletes, and 0.070 and 0.048 s in physically active subjects; data observed from the CMJ and CMJA, respectively).

Effects of countermovement depth on force and power output

Since they were related to our secondary aim, the effects of H_{cmd} on jumping mechanics were tested only on the pooled data. The results consistently reveal strong negative relationships between the H_{cmd} and both the F_{max} and P_{max} output in both groups and jump types (Figure 5). Specifically, a strong polynomial relationship between H_{cmd} and F_{max} was obtained in both jumps and its minimum was revealed well above the optimum H_{cmd}. As a result, F_{max} decreased over the most of the tested H_{cmd} range. Note also that F_{max} changed almost two-fold within the tested range. Finally, the strong negative relationships between H_{cmd} and P_{max} appeared to be approximately linear across both the subject groups and jump types. Note also that the regression line slopes are higher in the CMJA than in CMJ suggesting that the mechanical output of the CMJA was more sensitive to variations in H_{cmd}.

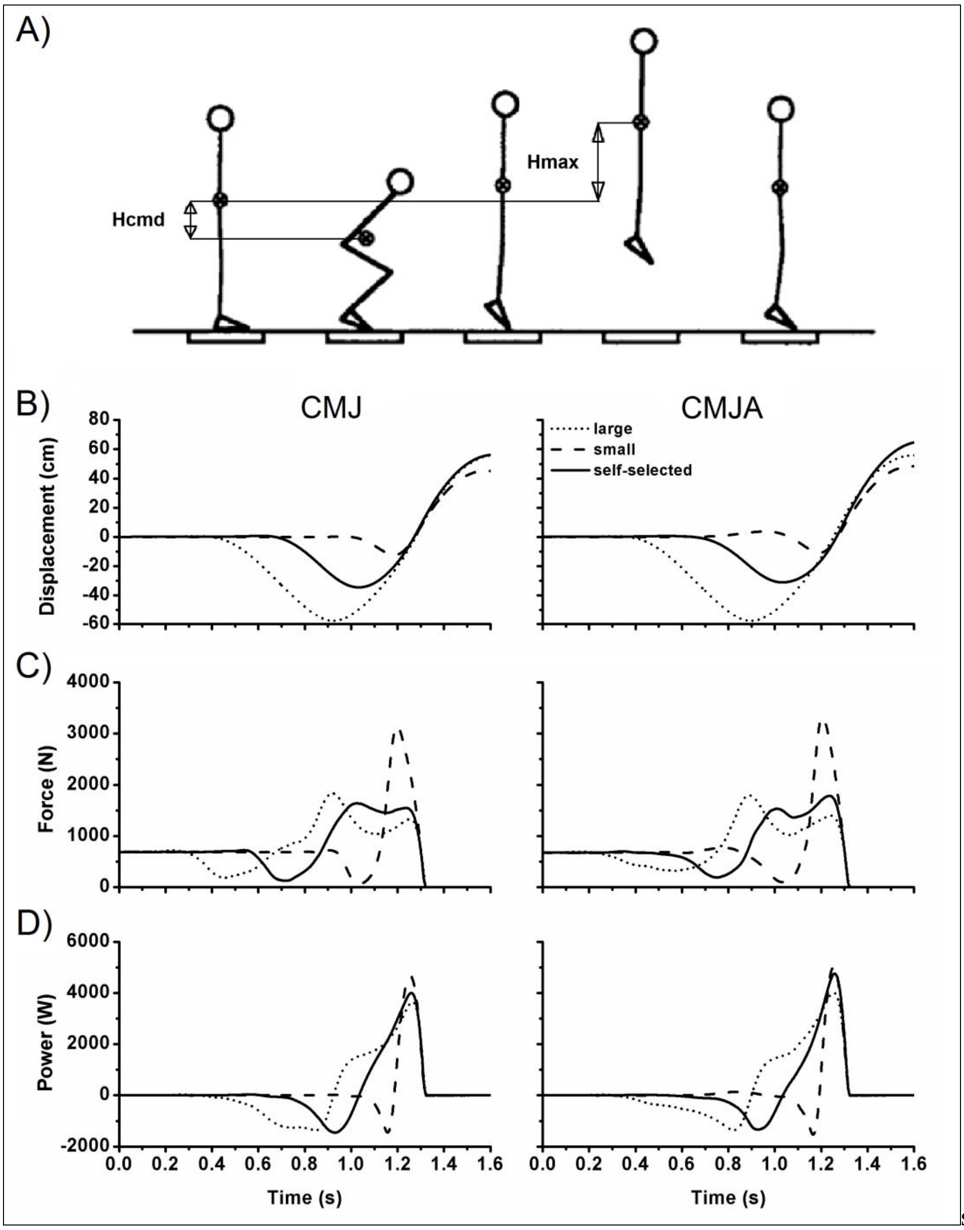

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Figure 1

(A) Illustration of the jump performed on a force plate:
H_{cmd} is the countermovement depth, while H_{max} is the jump height.
Lower panels show the representative time series of displacement of the center of mass (B), ground reaction force (C) and power output (D) recorded from the maximum countermovement jumps performed without (CMJ; left hand panels) and with an arm swing (CMJA; right hand panels).
The profiles are shown separately for the large, preferred and small countermovement depth.
The data are aligned with respect to the instant of the take-off.

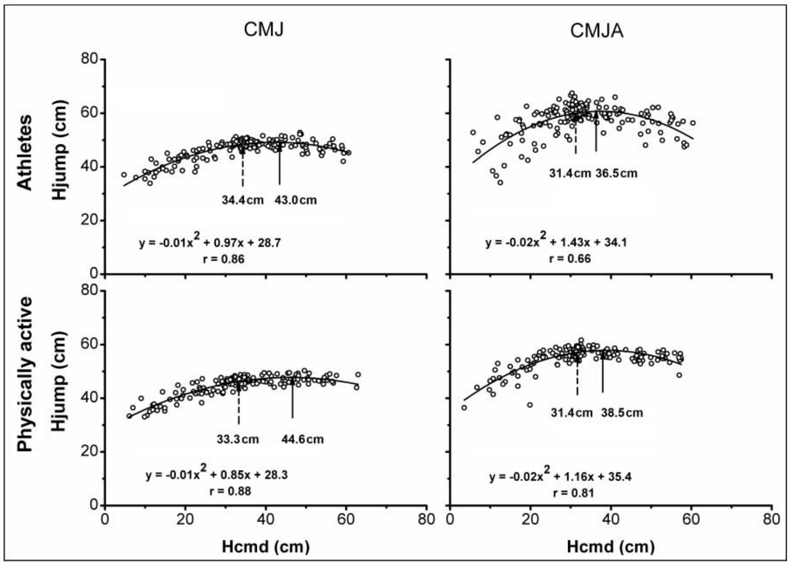

Figure 2

The relationship between the maximum jump height (H_{max}) and the countermovement depth (H_{cmd}) obtained from two jump types. The second-order polynomial regression models with the corresponding correlation coefficients are also shown. Dashed arrows indicate the preferred H_{cmd}, while the solid arrows indicate the optimum H_{cmd}.

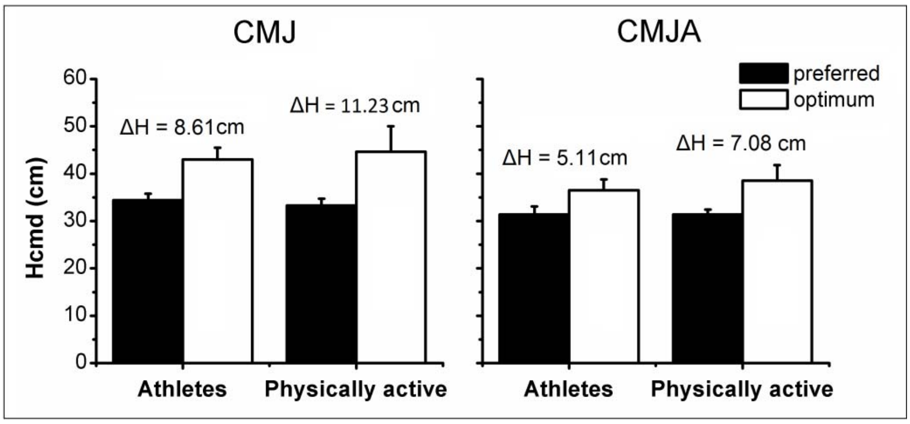

Figure 3

Averaged across the subjects preferred and optimum countermovement depth for two jump types (means with SD error bars The differences between the preferred and optimum values are shown above (all $p < 0.001$)

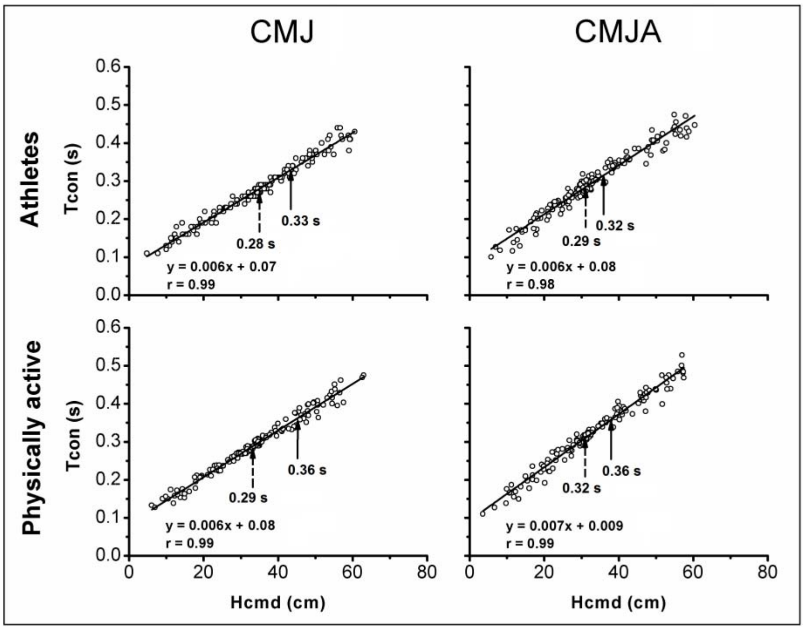

Figure 4

The relationship between the duration of the concentric jump phase (T_{con}) and the countermovement depth H_{cmd} obtained from two jump types. The linear regression models with the corresponding correlation coefficients are also shown. Dashed arrows indicate the preferred H_{cmd} while the solid arrows indicate the optimum H_{cmd}.

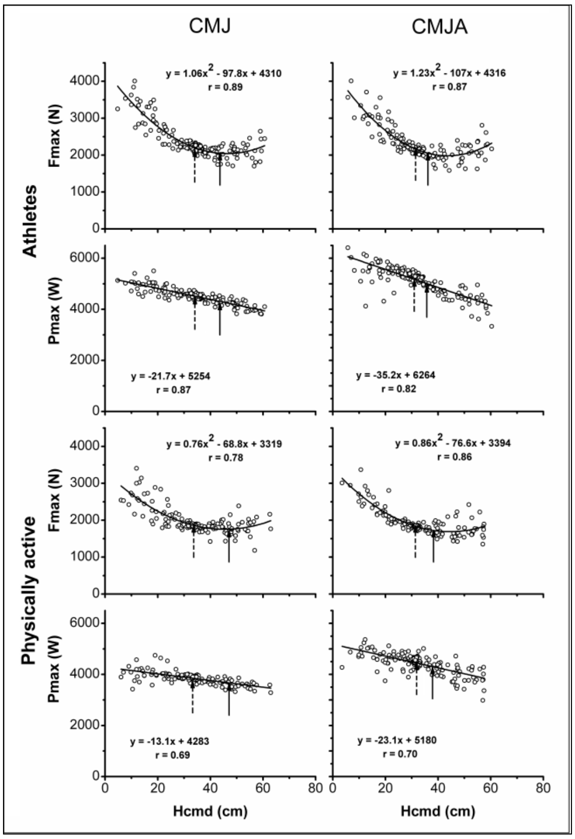

Figure 5

The relationship between the maximum force (F_{max}) and power (P_{max}) and the countermovement depth (H_{cmd}) obtained from two jump types. Either the second-order polynomial (for F_{max}) or linear regression models (for P_{max}) are presented with the corresponding correlation coefficients. Dashed arrows indicate the preferred H_{cmd}, while the solid arrows indicate the optimum H_{cmd}.

Discussion

The present study was designed with the main aim to compare the preferred countermovement depth (Hcmd) with the optimum one for maximization of the jump height (Hjump) in 2 distinctive groups of subjects. The obtained results were in line with our first hypothesis, since the preferred Hcmd was markedly smaller than the optimum Hcmd both in 2 subject groups and 2 jump types. In contradiction to our second hypothesis, however, the athletes that typically performed the jumps that were both high and quick, revealed smaller differences between the preferred and optimum Hcmd than the physically active individuals. Regarding our secondary aim, the results revealed a prominent negative effect of Hcmd on both the force and power output, despite the fact that the same effect on Hjump was relatively small.

Similarly to the findings of previous studies (Bobbert et al., 2008; Domire and Challis, 2007; Selbie and Caldwell, 1996), although the optimum Hcmd does exist, the polynomial regression models revealed that Hjump only slightly changes when Hcmd was varied within a relatively large interval. Nevertheless, the tested types of jumps showed that the subject of both groups consistently preferred a Hcmd magnitude that was markedly smaller than the optimum Hcmd that maximizes Hjump. Although the lost magnitude of Hjump due to the suboptimum Hcmd was only within the 0.1-1.2 cm range, the finding of the present study shed a new light on our understanding of the CMJ coordination strategies.

The discussed findings are in line with our previous study conducted on a single group of athletes (Mandic et al., 2015). However, the comparison of the present results obtained from 2 distinctively different subject groups allows for more elaborate discussion of the coordination strategies. Namely, our previous results observed in elite athletes that typically needed both to jump as high and as quickly as possible, guided us to a conclusion that their jumping pattern was based on a dual task strategy. Specifically, the tested subjects could have acquired a coordination pattern that traded a small portion of Hjump by selecting smaller Hcmd that allowed them to be markedly quicker. Not surprisingly, our data do show that smaller Hcmd leads to a quicker jump. In particular, that saved not only between 0.030 and 0.070 ms from the concentric jump phase, but probably much more from the eccentric one since the eccentric phase of countermovement jumps typically lasts much longer than the concentric one ((Markovic and Jaric, 2007b); see also Figure 1). Therefore, the selection of markedly smaller Hcmd could be the control strategy of athletes in a number of sport games that typically need to perform the jumps that are both high and quick. However, our data also show that the non-athletes who are not regular participants in sport games show even larger differences between the preferred and optimum Hcmd. Note that since the tested athletes were markedly taller that the physically active participants, the same differences would be even more prominent if normalized for the differences in body height. This finding speaks against the hypothesized 'dual-task' strategy and, therefore, the preferred Hcmd that is prominently smaller than the optimum one which could be a general property of the coordination of the CMJ. Apparently, further research is needed to explain the observed phenomenon. A plausible alternative explanation could be based on minimization of effort (Ganesh et al., 2010) or work and energy (Alexander, 1997). Namely, the selected control strategy could considerably save on the effort and energy expenditure, while losing a relatively small part of the Hjump magnitude. An even more general question could be whether the same strategy could be generalized to other rapid movements that include a preceding countermovement, such as throwing, punching and even running.

Despite its small effect on maximum Hjump, the differences between the preferred and optimum Hcmd were as large as 5-12 cm, depending on the jump type and subject group. Taken together with typical variability of Hcmd of approximately 3-10 cm observed from consecutive jumps of the same subjects (Mandic et al., 2015; Markovic et al., 2014), such differences proved to result in prominent changes in the directly measured force and power output. Therefore, the present study adds to the evidence that the variations in Hcmd decouple jumping performance from the muscle force and power output (Bobbert et al., 2008; Feeney et al., 2016; Mandic et al., 2015; Markovic et al., 2014). Specifically, it shows that the selected control strategy based on a relatively short preferred Hcmd provides considerably higher force and power output than observed in the same jumps conducted from the optimum Hcmd that maximize Hjump.

To conclude, the present study reveals an element of control strategy that has been neglected in routine training, testing and research based on natural maximum vertical jumps performed with a preceding countermovement. Namely, the preferred Hcmd is markedly below its optimum value that maximizes Hjump, although neither the subjects nor the experimenters are typically aware of that. Furthermore, the comparison of the data obtained from 2 distinctive subject groups speaks against the hypothesis that the recorded behavior could originate from the jumps being a dual task resulting from a trade-off between the jumping height and jumping quickness typically required in a number of sport competitions. Although one could also assume that the minimization of the effort and energy expenditure could also play a role, the cause of such a control strategy remains elusive. Besides the motor control issues, the researchers and professionals in the field should be aware that when instructed to jump as high as possible, the subjects consistently select a considerably smaller Hcmd than the optimum one, as well as that the altered Hcmd markedly confounds the frequently used assessment of the leg muscle strength and power from the recorded Hjump. Both of those findings should be of apparent importance for interpretation of the outcomes of routine testing procedures based on maximum vertical jumps.

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