RELATIONSHIP BETWEEN KNEE EXTENSOR MUSCLE STRENGTH AND MOVEMENT PERFORMANCE: THE EFFECT OF LOAD AND BODY SIZE

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Abstract:

The main aim of the present study was to evaluate the effect of external loading on the relationship between leg muscle strength and vertical jump performance. Sixty-six physically active men performed maximal countermovement jumps (CMJ) under five loading conditions: body weight (BW), negative loads (85% BW and 70% BW) and positive loads (115% BW and 130% BW), on a force plate. CMJ was followed by the measurement of subjects' maximal concentric knee extension torque at $60^{o}s^{-1}$ by an isokinetic dynamometer. The relationship between knee extensor strength and jumping performance with various loads was assessed by Pearson's correlation coefficients and partial correlation coefficients after controlling for body mass. Knee extensor muscle strength correlated significantly (r=.78-.79; all p<.01) with peak power output during CMJ under all loading conditions. Considerably lower correlation coefficients (r=.18-.43; p=.01-.15) were observed between knee extensor strength and CMJ height under all loading conditions, which tended to be higher after the effect of body mass had been removed (r=.37-.51; all p<.01). These results contradict the general belief that an increase in external load is associated with the increased role of leg muscle strength in maximizing power output and jump height. Furthermore, the results suggest that relative strength is a better predictor of jumping performance than absolute strength, independently of external loads used.

Key words: *muscle power, body size, force-velocity relation, movement performance*

Introduction

One of the fundamental mechanical properties of skeletal muscles is the force-velocity-power relationship (Hill, 1938). Based on that relationship, power output of a skeletal muscle depends on both muscle force (i.e. external load) and velocity of muscle shortening. Since these two mechanical variables are inversely related, power output under higher external loads is more dependent on muscle strength and *vice versa*. Given that muscle power output is of decisive importance for successful performance in various athletic and sporting activities (Cronin & Sleivert, 2005), we may hypothesize that the heavier the load that an athlete has to overcome during competition, the more important is the muscle strength for power production and performance. This conjecture, although indirectly supported by some studies (e.g. Markovic, 2006), is likely to be valid only if the movement kinematic pattern (and, consequently, force-length relationship of the involved muscles) remains constant under different loading conditions. Interestingly, our recent studies (Markovic & Jaric, 2007; Markovic, Vuk, & Jaric, 2011; Vuk, Markovic, & Jaric, 2012) indicate that both athletes and non-athletes change their movement kinematic pattern (i.e. depth of a countermovement) during performance of maximum vertical jumps with different loads. Specifically, an increase in external load resulted in a systematic decrease in the depth of a countermovement and *vice versa* (Markovic & Jaric, 2007; Markovic, et al., 2011; Vuk, et al., 2012). As a re-sult, changes in flexion angles in all three major leg joints lead to changes in leverage of leg extensors, which inevitably affects force and power output of leg extensors during CMJ. Therefore, it is possible that the relationship between leg extensors' strength and power output or performance during vertical jumping with various loads might *not increase* with an increase in the external load applied, as expected from simple force-velocity-power relations. To our best knowledge, this conjecture has not been systematically tested for human vertical jumping. This is surprising, given that vertical jumps with various loads have been frequently used in evaluating the human lower-body neuromuscular function, as well as in determining the optimal training strategies for enhancing the lower-body power production and performance (e.g. heavy-load strength training vs low-load power training; see Newton & Dugan, 2003).

In the present study, we addressed this issue by examining the effect of external loading on the relationship between leg muscle strength and vertical jump performance (power output and jump height). In line with a simple force-velocity-power relationship, we hypothesized that an increase in external load will be associated with an increased role of leg muscle strength in maximizing power output and jump height. Given that the relationship between muscle strength and power production or performance in functional human movements could be influenced by the individual's body size (Jaric, 2003; Jaric, Mirkov, & Markovic, 2005), we also took into account this potentially important confounding factor.

Methods

Subjects

For the purpose of this study, we recruited a sample of 66 young and healthy men (age: 22±4 years; body mass: 79.0±8.7 kg; stature: 181.7±7.1 cm; percentage of body fat: 12.2±4.5%; mean±SD). Forty-eight of them were physical education students, and the remaining 18 participants were athletes from different sports. All participants had previous experience in performing CMJs. Furthermore, a recent study has shown that the reliability of the mechanical variables recorded during CMJs with different loads is similar in athletes and non-athletes (Markovic, et al., 2011). Thus, we were confident that the differences in training background between athletes and non-athletes in this study would not affect our main results. All participants gave a written informed consent to participate in the experiments, which was in accordance with the Declaration of Helsinki and approved by the local Institutional Review Board.

Testing procedures

After a standardized warm-up that included light aerobic activity (5 minutes), dynamic stretching, callisthenics and 10 submaximal CMJs, each subject performed three consecutive CMJ trials under each of the five loading conditions (see further text) in random sequence. No specific instruction was given regarding the depth of the countermovement. One minute of rest was allowed between the consecutive jumping trials, and 2-3 minutes between the consecutive loading conditions (Markovic & Jaric, 2007). During the familiarization session conducted prior to the experimental testing, each subject performed several probationary CMJs under each of five loading conditions.

External loading during CMJ was applied by means of a pulley system that mimics either an increase or a decrease of the subjects' body weight (BW). The details of the system have been described in recent studies by Markovic and Jaric (2007) and Markovic et al. (2011). In brief, the system uses four long rubber bands (resting length: 8 m) that provide an approximately constant pulling force within the range of motion of the centre of mass during the jump (see further text). The rubber bands are connected to a light and rigid low-friction cable, which is then attached to a modified weightlifting belt worn by a subject. The loading system enabled the performance of CMJs without any particular movement constraints when applied to pull subjects either vertically upward ('negative load') or vertically downward ('positive load').

We applied the following five loading conditions: 'zero load' (100% BW), negative loads that unloaded the subjects by 15% (85% BW) and 30% (70% BW) of their BW, and positive loads that loaded the subjects by additional 15% (115% BW) and 30% (130% BW) of their BW (Markovic & Jaric, 2007). A fine tuning of the applied loads was done by weighing the loaded subjects by a force plate. To increase/decrease the subject's BW by 15% and 30%, the elastic bands were on average stretched to approximately 150% and 200% of their resting length (i.e. 12 m and 16 m, respectively). Note that during the performance of CMJs with different loads the subjects lower their centre of mass by 0.2-0.4 m (Markovic & Jaric, 2007), which corresponds to only 1% to 3% of the total elastic bands' stretch. As a result, one could consider the applied load forces to be approximately constant during the take-off phase (Markovic & Jaric, 2007). Further verification based on the differences in the recorded weight between the upright and squatting position revealed the values below 10 N for all participants and loading conditions.

The CMJs were performed on a force plate (Kistler type 9290AD, Winterthur, Switzerland; sampling frequency 500 Hz) mounted according to the manufacturer's specifications. The following mechanical variables were calculated from the recorded vertical component of the ground reaction force: vertical displacement of the body mass centre to the lowest point of the eccentric jump phase, peak vertical force during the concentric jump phase, and peak power output during the concentric jump phase. Position of the centre of mass was obtained via double integration of the vertical acceleration data measured by the force plate and CMJ height, which was calculated from the difference between the maximum and starting level of the centre of mass. The power output was calculated as a product of the vertical component of the ground reaction force and the velocity of the centre of mass.

Vertical jumping was followed by the measurement of the subject's maximal concentric quadriceps strength (non-dominant leg only) at 60°s^{-1} by an isokinetic dynamometer (System 4, Biodex

Corporation, Shirley, New York, USA). The subject was strapped into the chair, using the lateral femoral condyle as an anatomical reference for the axis of rotation. The length of the lever arm was individually determined and the resistance pad was placed proximally to the medial malleolus. Gravity correction was applied following direct measurements of the mass of the lower limb-lever arm system at 30° knee extension. The range of motion covered the interval from 90° of flexion to 10° of extension (0° equals full knee extension). The maximum value of the peak concentric knee extension torques recorded over five consecutive contractions was used for data analysis.

Statistical analyses

Descriptive statistics indicators were calculated for all experimental variables as means and standard deviations. The relationship between knee extensor muscle strength and jumping performance (i.e. peak power output and jump height) during vertical jumping with various loads was assessed by Pearson's product moment correlation coefficients (r). Since body size is known to influence the relationship between muscle strength and movement performance (Jaric, 2003; Jaric, et al., 2005; Markovic, 2006), we also calculated partial correlation coefficients (r_p) between knee extensor muscle strength and jumping performance, controlling for body mass. A simple sign test was used to test the significance of differences in correlation coefficients between knee extensor strength and vertical jump performance before and after removing the effect of body mass. The strength of correlation coefficient was determined based on the classifications outlined by Cohen (1988) where r=.10-.29 has a small effect, r=.30-.49 has a moderate effect and r≥.50 has a large effect. The level of statistical significance was set at p<.05.

Results

The descriptive data for the selected kinematic and kinetic jumping variables, obtained in the five loading conditions, are depicted in Table 1. The average (±SD) knee extensor peak torque generated by the subjects was 229.8±48.1 Nm. Knee extensor muscle strength correlated significantly with peak power output during CMJs, and the strength of this relationship was consistent across all loading conditions (r=.78-.79; all p<.001; see Figure 1). When controlled for body mass, the corresponding correlation coefficients did not change significantly (r_p=.62-.65; all p<.001; see Table 1). Considerably lower Pearson's correlation coefficients (r=.18-.43; p=.01-.15) were observed between knee extensor muscle strength and CMJ height in all loading conditions (Figure 2). Removing the effect of body mass tended to increase (sign test: Z=1.79; p=.07) the correlation coefficients between knee extensor muscle strength and CMJ height in all loading conditions (r_p=.37-.51; all p<.01; see Table 1).

Table 1. Peak power, jump height, and depth of countermovements (mean±SD) recorded during CMJs with different loads, and their zero-order (r) and partial correlations (r_p; 95% confidence intervals in brackets) with knee extensor muscle strength, after controlling for body mass

	Loading conditions				
	70% BW	85% BW	100% BW	115% BW	130% BW
Peak power (W)	5672±1100	4863±972	4225±776	3628±663	3224±565
r	.79	.78	.78	.79	.78
r_p	.65 (.48-.77)	.63 (.46-.76)	.62 (.44-.75)	.65 (.44-.75)	.65 (.48-.77)
Jump height (cm)	99.8±13.6	66.9±7.7	47.3±5.7	34.2±4.3	26.8±4.5
r	.43	.31	.30	.25	.18
r_p	.51 (0.31-0.67)	.46 (0.25-0.63)	.46 (0.25-0.63)	.42 (0.20-0.60)	.37 (0.14-0.56)
Depth of countermovements (cm)	-45.6±10.9	-38.9±5.9	-31.9±5.7	-25.6±3.9	-20.5±3.8

BW – body weight; CMJ – countermovement jump; r – Pearson's correlation coefficient; r_p – Pearson's partial correlation coefficient after removing the effect of body size.

Discussion and conclusions

In the present study we examined the effect of external loading on the relationship between knee extensor muscle strength and vertical jump performance while taking into account the influence of body size. The main finding of the present study is that an increase in external loading during vertical jumping *is not* associated with the increased role of leg muscle strength in the maximization of jumping performance. In particular, knee extensor muscle strength explained ~60% of variance in peak jumping power, regardless of the applied loading conditions during CMJ. When jump height was used as a performance measure, the amount of shared variance with knee extensor muscle strength was considerably lower and ranged between 3% (the heaviest load) and 18% (the lightest load). Our findings contradict our hypothesis, which was based

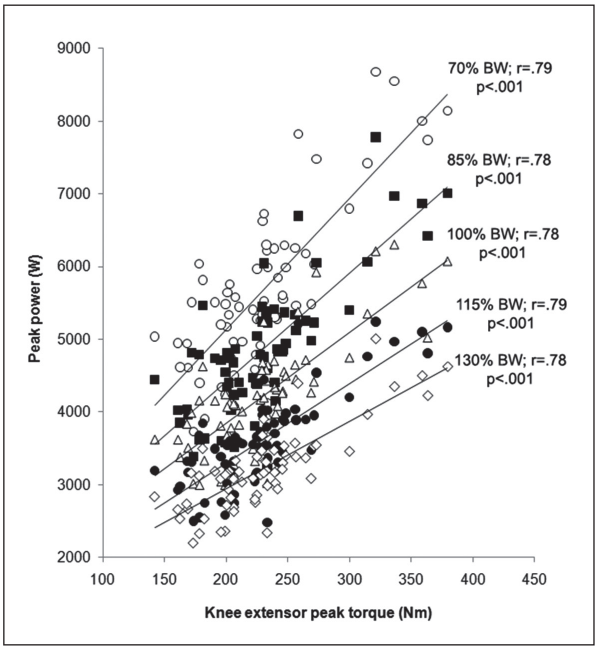

Figure 1. Relations between knee extensor peak torque and countermovement jump peak power output at 70% BW (open circles), 85% BW (filled squares), 100% BW (open triangles), 115% BW (filled circles), and 130% BW (open diamonds). BW – body weight.

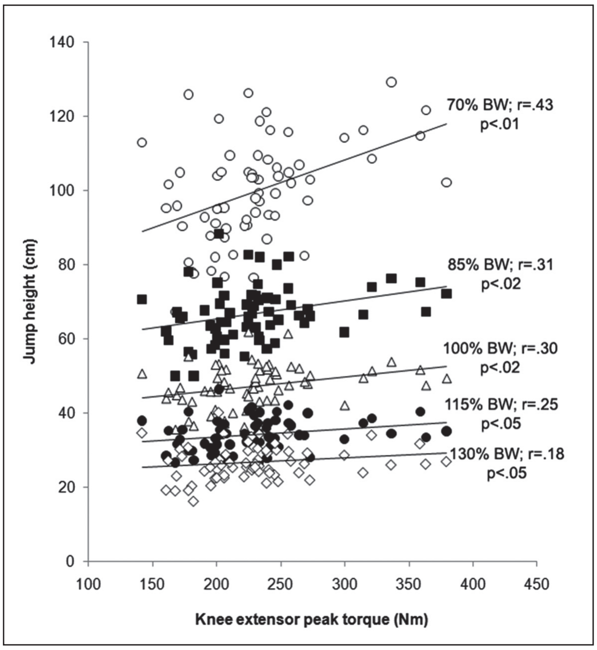

Figure 2. Relations between knee extensor peak torque and countermovement jump height at 70% BW (open circles), 85% BW (filled squares), 100% BW (open triangles), 115% BW (filled circles), and 130% BW (open diamonds). BW – body weight.

on the well known force-velocity relation. Namely, it was generally expected that the relationship between muscle strength and functional movement performance increases with increased external loads (e.g. Cormie, McCaulley, Triplett, & McBride, 2007; Baker, 2001a,b). Possible explanation for this unexpected finding could be related to the altered jumping pattern induced by external loading (for review, see Jaric & Markovic, 2013), as evidenced by the load-associated alteration in the depth of countermovements (Table 1). In particular, CMJs allow subjects to modify depth of countermovements during the eccentric phase of jump, thereby affecting the activation pattern of different muscle groups and, consequently, their overall contribution to the power output and performance (Jaric & Markovic, 2013; Markovic & Jaric, 2007; Vuk, et al., 2012). Interestingly, this behaviour appears to be universal for CMJs, i.e. independent of the subject's level of strength and skill (for review, see Jaric & Markovic, 2013). Further studies are needed to verify our main findings.

Aside from the effect of external loading on the relationship between leg muscle strength and vertical jump performance, the magnitude of this relationship also needs to be discussed. Only a few studies examined the relation between leg extensor muscles strength and CMJ power (Haff, et al., 1997; Carlock, et al., 2004), and reported conflicting findings. Haff et al. (1997) measured maximal force during isometric clean pulls from mid-thigh and CMJ peak power in eight trained men, and reported moderate but statistically insignificant correlation (r=.47, p>.05). Isometric testing and a small sample size may explain the lack of the significant relationship between strength and power measures. Conversely, Carlock et al. (2004) reported a very high correlation (r=.91) between 1RM squat and CMJ peak power in 64 weightlifters. It should be noted that the authors included both men and women in their study, which likely increased the variability of the data and, consequently, the strength of correlation. Our findings are in favour of this study and suggest that maximum strength is strongly associated with jumping power.

Contrary to power output, the relationship between leg extensor muscle strength and vertical jump height has been extensively studied. The results of those studies have often provided inconsistent findings; while some authors found strong relationship between muscle strength and jump height (Hakkinen, 1991; Wisloff, Castagna, Helgerud, Jones, & Hoff, 2004), others found mode-rate to weak relationship (Jaric, Ristanovic, & Corcos, 1989; Ugarkovic, Matavulj, Kukolj, & Jaric, 2002), or no relationship at all (Blackburn & Morrissey, 1998). Such inconsistencies could be ascribed to methodological issues. Namely, previous research used (1) different types of dynamometry for leg extensor strength assessment – isokinetic dynamometry (Blazevich & Jenkins, 1998), isoinertial dynamometry (e.g. 1RM leg press; Liebermann & Katz, 2003; or 1RM back squat; Markovic, 2006), or isometric dynamometry (e.g. knee extension; Jaric, et al., 1989); (2) different types of jumps like countermovement jumps (e.g. Wiklander &

Lysholm, 1987; Ugarkovic, et al., 2002; Wisloff, et al., 2004; Nuzzo, McBride, Cormie, & McCaulley, 2008) vs squat jumps (e.g. Malliou, Ispirlidis, Beneka, Taxildaris, & Godolias, 2003; Sipila, et al., 2004; Copic, Dopsaj, Ivanovic, Nesic, & Jaric, 2014) and (3) subjects with different training history (for review, see Fahey, 2001).

We have also observed a tendency towards an increase in correlation coefficients between knee extensor muscle strength and jump height in all loading conditions after partitioning out the effect of body size. Theoretical predictions and empirical evidence suggest that body size relates differently to muscle strength vs vertical jump height (Jaric, 2002; Markovic & Jaric, 2004). In particular, when muscle strength is expressed as torque (as in the current study), it should be proportional to individuals' body mass (Jaric, 2002). In contrast, vertical jump height as a performance measure should be body-size independent (Markovic & Jaric, 2004). In such cases, correlation between muscle strength and functional performance increases when strength data are appropriately normalized for body size (Jaric, 2003). Hence, the observed results can be viewed as expected. Furthermore, these results support the idea that relative strength is a better predictor of jumping performance than absolute strength, independently of external load used.

Our study also had some limitations that should be discussed. First, we have used isokinetic dynamometry for knee extensor strength assessment. From the point of view of the principle of specificity, knee extension on an isokinetic apparatus (i.e. low-velocity, concentric-only, single-joint, open kinetic chain movement) has little resemblance with CMJs (high-velocity, SSC, multi-joint, closed kinetic chain movement). However, this approach does ensure a high reproducibility of strength assessment, regardless of subjects' fitness level or skill. Furthermore, it is one of the most often used methods for analysing the strength-performance relationship in sports and exercise sciences (Wilson & Murphy, 1996; Jaric, 2002). Nonetheless, future studies should test the validity of our results using more 'functional' multi-joint strength movements like squats. Furthermore, it should be stressed that we tested a relatively homogeneous group of individuals who were not only of the same sex and of similar age, but they were all physically highly active. Such homogeneity decreases both the variability in the analysed performance variables and their inter-relationships. Hence, our results need to be verified with other populations as well.

To conclude, contrary to the predictions based on force-velocity-power relations, our results indicate that the relationship between leg muscle strength and vertical jump performance (peak power and jump height) is generally independent of the external load applied during jumping. Furthermore, the results suggest that relative strength could be a better predictor of jumping performance than absolute strength. From a practical point of view, these results support the importance of relative leg strength in the maximization of vertical jump performance (Cronin & Sleivert, 2005). Our results also indicate that by increasing external loads, the vertical displacement decreases, which affects the leverage of leg extensors and muscle's force-length relation. This could bring into question the validity of using the load-power relation during CMJs for defining the optimal loading that maximizes power output for particular groups of athletes. Instead, a squat jump from the fixed squat position should be used for such purposes.

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