OPERATING LENGTH AND VELOCITY OF HUMAN M. VASTUS LATERALIS FASCICLES DURING VERTICAL JUMPING

Maria Elissavet Nikolaidou[1], Robert Marzilger[2,3], Sebastian Bohm[2,3], Falk Mersmann[2,3] and Adamantios Arampatzis[2,3]

School of Physical Education & Sport Science, National and Kapodistrian University of Athens, Athens, Greece[1]
Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Berlin, Germany[2]
Berlin School of Movement Science, Berlin, Germany[3]

The purpose of this study was to investigate the operating length and velocity of the human vastus lateralis (VL) fascicles regarding force and power generation during vertical jumping in vivo. Compared to the SJ, the VL fascicles operated on a more favourable portion of the force-length curve and more disadvantageous portion of the force-velocity curve in the CMJ, indicating a reciprocal effect of force-length and force-velocity potentials for force generation. The mean fascicle shortening velocity in the CMJ was closer to the plateau of the power-velocity curve, which resulted in a greater power-velocity potential. We provided for the first time evidence for a cumulative effect of three different mechanisms - i.e. greater force-length potential, greater power-velocity potential and greater muscle activity - for an advantaged power production in the CMJ.

KEY WORDS: Force-length-velocity potential, power-velocity potential, activation.

INTRODUCTION: Humans achieve greater jump height during the counter movement jump (CMJ) compared to the squat jump (SJ) (Bobbert et al, 1996). Jump height is determined by the total mechanical work performed by the lower extremities muscle-tendon units (Anderson & Pandy, 1993), which most likely relates to the muscle forces generated during the propulsion phase. However, the crucial difference is the mean mechanical power output achieved during the propulsion phase. In the CMJ the mean mechanical power output is about 47% higher compared to the SJ (Bobbert, 2014). Beyond muscle activation, force and power production is also dependent on the force-length and force/power-velocity potentials of the muscle. Therefore, possible differences between SJ and CMJ with regard to fascicle length and fascicle shortening velocity of the contributing muscles during the propulsion phase may influence the muscle force and power production at a given muscle activation. Musculoskeletal models predict a major contribution of the vastii muscles to mechanical energy production during both SJ and CMJ (Anderson & Pandy, 1993; Bobbert, 2014). To the best of our knowledge, the fascicle behaviour, operating length and shortening velocity of the vastii muscles during SJ and CMJ in vivo have not been investigated yet. Therefore, our current understanding of how muscle mechanics might be related to the increased performance in the CMJ compared to the SJ is still widely deficient. In the current study we measured the vastus lateralis (VL) fascicle length and electromyographic activity (EMG) as a representative of the mono-articular knee extensor muscles during SJ and CMJ. The purpose of this study was to investigate the operating length and velocity of the VL muscle fascicles regarding force and power generation during SJ and CMJ in vivo. We predicted a more favourable operating length and shortening velocity closer to the optimum for force and power generation, respectively, for the CMJ compared to the SJ.

METHODS: On the first day of the experimental protocol, the VL force-fascicle length relationship for 17 participants (age, 27.0 ±4.1 years; body mass, 76.8 ±8.8 kg; height, 179.5 ±6.2 cm) was experimentally assessed during eight maximal isometric voluntary knee extension contractions (range: 20 to 90° knee joint flexion angle in 10° intervals). The patellar tendon force during the MVCs was calculated by dividing the knee joint moment with the

patellar tendon moment arm. For the calculation of the knee joint moment the axes misalignment (Arampatzis et al., 2004) and the co-activity of the hamstring muscles were included. The patellar tendon moment arm was measured using MRT-images (G-Scan, 0.25 T, 3D HYCE (GR) sequence, Esaote). The VL fascicle length changes during the MVCs were measured using ultrasound images captured with a 10cm-linear array probe at 43Hz (10 MHz, Esaote MyLab^{TM}60) and analyzed using a Matlab custom-made tracking interface. The maximal shortening velocity of the VL fascicle was determined using muscle-specific values a_{rel}=0.34 and b_{rel}=4.03s^{-1} (Miller et al, 2012), resulting in a calculated maximal VL shortening velocity (V_{max}) of 11.85L_0/s. Subsequently, the force-velocity relationship of the VL fascicles was described following the classical Hill equation (1938).
On a 2nd day of the protocol, the VL fascicle length and EMG-activity of VL, vastus medialis (VM), rectus femoris (RF) and biceps femoris (BF) were measured during 5 SJs and 5 CMJs using the ultrasound and a wireless electromyography device (Myon m320RX system, 1000 Hz). Further, the kinematics of the right leg (Vicon-system, 250 Hz) and the ground reaction forces (1000Hz) were examined. The vertical take-off velocity of the centre of mass (CM) during the jumps was calculated by integration of the vertical GRF over the time. Mechanical power applied to the CM was determined as the product of vertical GRF and vertical centre of mass velocity. The VL fascicle length was filtered using a 2nd low pass Butterworth filter (6Hz) and the VL fascicle velocity was then calculated as the first derivative of the fascicle length over the time. For statistical analysis of the data, the average values of 5 trials of each condition were used. Statistics included a paired t-test to examine possible differences in all investigated parameters between SJ and CMJ. Level of significance was set to α=0.05.

RESULTS: The experimentally assessed L_0 of the VL muscle and F_{max} applied to the patellar tendon at L_0 were 9.4±1.1 cm and 4923±929 N. The estimated V_{max} and the optimal shortening velocity (V_{opt}) to generate maximal power (P_{max}) of the VL were 111.4±13.4 cm/s and 37.1±4.5 cm/s. Jump height, mean mechanical power applied to the center of mass and average EMG activity of all investigated leg muscles during the propulsion phase were significantly higher in CMJ compared to SJ (Table 1). The fascicle length at the beginning of the propulsion phase ($_{begin}$) as well the shortening of the VL fascicles during that phase were larger in the SJ, however the mean and the achieved maximum shortening velocity were larger in the CMJ (Table 1).

Table 1
Selected Parameters during the Propulsion Phase obtained during SJ and CMJ (mean values ± standard deviation).

Parameter	SJ	CMJ	p value
Jump height [cm]	28.0 ± 3.6	29.5 ± 4.3	0.009
Mean mechanical power [Watt/kg]	15.98 ± 3.37	25.02 ± 4.48 *	0.002
Mean EMG-activity of VL [%, normalized to MVC]	107.6 ± 43.9	123.4 ± 48.6	0.001
Mean EMG-activity of VM [%, normalized to MVC]	124.2 ± 56.4	140.5 ± 62.4	0.000
Mean EMG-activity of RF [%, normalized to MVC]	119.3 ± 40.8	143.1 ± 56.2	0.001
Mean EMG-activity of BF [%, normalized to MVC]	37.8 ± 36.3	45.0 ± 25.4	0.003
Fascicle length $_{begin}$ [cm]	13.2 ± 1.1	12.1 ± 1.1	0.001
Fascicle shortening [cm]	6.4 ± 1.3	5.3 ± 1.2	0.000
Mean shortening velocity [cm/s]	13.8 ± 3.3	17.6 ± 3.9	0.010
Maximum shortening velocity [cm/s]	35.4 ± 8.8	41.3 ± 8.5 *	0.001

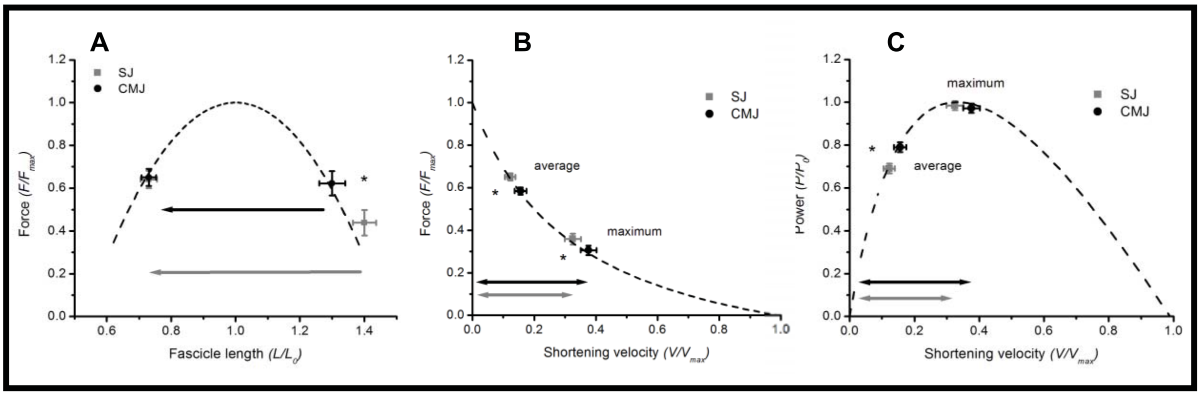

Figure 1: Operating length (A) and velocity (B & C) of VL fascicles onto the normalized force-length, force-velocity and power-velocity curves during SJ and CMJ (mean values ± standard error). Force is normalized to the F_{max} obtained during the MVCs, fascicle length to the experimentally determined L_0, fascicle shortening velocity to the estimated V_{max} and power to the P_{max} predicted from the force-velocity curve and fascicle shortening velocity to the estimated V_{max}. The two arrows indicate the range of the operating length and velocity of the VL fascicles during the propulsion phase of SJ and CMJ.
***: Statistically significant difference between SJ and CMJ ($p<0.05$).**

Figure 1A shows that the VL fascicles operated closer to the L_0 in the CMJ than during the SJ during the propulsion phase which resulted in a significantly higher ($p=0.001$) average force-length potential (fraction of VL F_{max} according to the force-length relationship) for the CMJ. The larger mean shortening velocity during the propulsion phase in the CMJ resulted in a significantly lower force-velocity potential (fraction of VL F_{max} according to the force-velocity relationship) compared to the SJ ($p<0.001$, Figure 1B). Further, the mean shortening velocity in the CMJ was closer to V_{opt} which resulted in a significantly higher average power-velocity potential (fraction of VL P_{max} according to the power-velocity relationship) during the propulsion phase, while the maximum shortening velocity was very close to V_{opt} during both jumps without any differences in maximum power-velocity potential (Figure 1C).

DISCUSSION: The current investigation, based on an in vivo assessment of the human VL fascicle length and shortening velocity during SJ and CMJ, provides for the first time evidence that both the muscle intrinsic force-length and power-velocity relationships as well as muscle activation contribute to the marked differences in the mean mechanical power output (56%) between the two jumps. In both jumps the initiation of the push-off phase was performed at the same knee angle (i.e. same length of the VL muscle-tendon unit), however the fascicle length of the VL was on average 1 cm shorter in the CMJ compared to the SJ. This difference can be explained by tendon compliance and the higher active state of the VL muscle in the CMJ. The consequence was that, at the same length of the muscle-tendon unit, the force generating potential of the VL muscle was higher in the CMJ due to the force-length relationship. This means that at the time of the initiation of the push-off phase both a higher activation level and a higher force-length potential of the VL muscle promoted muscle force and power generation in the CMJ compared to SJ. During the propulsion phase the VL fascicles first operated toward optimal length for force generation in both jumps and then in the ascending part of the force-length curve showing a substantial shortening. As the VL muscle underwent an active shortening and performed mechanical work, it operated on a more favourable portion of the force-length curve and on a more disadvantageous portion of the force-velocity curve in the CMJ compared to the SJ, indicating a reciprocal effect of force-length and force-velocity potentials for muscle force generation. This behaviour illustrates that during the push-off phase the increased activity of the VL muscle in the CMJ and not muscle intrinsic force-length-velocity relationships facilitate muscle force generation and can explain the moderate differences in jump height between SJ and CMJ. Therewith our experimental data confirm predictions from modelling-studies reporting that the higher

activation of the extensor muscles is the responsible mechanism for the higher jumping height in CMJ (Bobbert and Casius, 2005).
The shortening velocity of the VL fascicle ranged from the ascending part of the power-velocity curve to the optimal velocity for power generation in both jumps. The mean velocity values of the VL fascicles relative to the V_{max} during the push-off phase were 16% for the CMJ and 12% for the SJ. The consequence of this behaviour (i.e. operation of the VL fascicle shortening velocity in the ascending part of the power-velocity curve) during the propulsion phase was a more favourable average power potential in the CMJ. The larger mean shortening velocity of the VL was closer to the plateau of the power-velocity curve in CMJ and resulted in a 15% greater average power potential in the push-off phase of the CMJ. Taken into consideration that also the force-length potential and the EMG activity of the VL during the propulsion phase were higher in the CMJ (7% and 15% respectively) and that both a more favourable force-length potential and activation enhance the power output of a muscle (Azizi and Roberts 2010), we provide evidence for a cumulative effect of three different mechanisms for an advantaged power production in the CMJ. Consequently, our results lend strong support to the important role of intrinsic mechanical mechanisms of the VL muscle (i.e. force-length and power-velocity relationships) as well as muscle activation level regarding the clear increase in mean mechanical power applied to the centre of mass in the CMJ compared to the SJ.

CONCLUSION: The findings of the current study lead us to conclude that three important mechanisms for increased muscle power production were favourable in CMJ compared to SJ. During the propulsion phase of the CMJ (a) the fascicles of the VL muscle operate at lengths near the plateau of the force-length curve, (b) the fascicles operate at shortening velocities near to the optimal velocity for power production and (c) the VL muscle is subjected to a higher activation level than during the SJ. The findings help researchers and practitioners to understand the neuromuscular reasons for the different performance output between SJ and CMJ.

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