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Communication

No Association between Jump Parameters and Tissue Stiffness in the Quadriceps and Triceps Surae Muscles in Recreationally Active Young Adult Males

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Abstract: While the main contributor for drop jump (DJ) performance is the calf muscle–tendon unit (MTU), for countermovement jump (CMJ) performance, it is the quadriceps MTU. However, to date, it is not clear if the muscle and/or tendon stiffness of the respective MTUs can be related to DJ or CMJ performance. Therefore, the purpose of this study was to investigate the relationships between DJ and CMJ performance parameters and tissue stiffness (i.e., muscle stiffness, tendon stiffness) of the calf MTU and quadriceps MTU, respectively. Consequently, with 16 healthy volunteers, the tissue stiffness of the gastrocnemius medialis (GM), gastrocnemius lateralis (GL) Achilles tendon (AT), vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), and patellar tendon (PT) were recorded with a Myoton device. Moreover, DJ and CMJ performances were assessed with a force plate. The alpha level was set to 0.05. Pearson correlation coefficients revealed no significant association between DJ performance and GM, GL, or AT stiffness (−0.07 to 0.24; $p > 0.05$). Similarly, no association was found between CMJ performance parameters and VM, VL, RF, or PT stiffness (−0.13–0.36; $p > 0.05$). According to our results, other variables, such as jump technique, body weight, or strength, were likely play a more important role in DJ and CMJ performance.

Keywords: jumping; stiffness; Myoton; muscle; tendon

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1. Introduction

The jumping ability of an individual is a predictor for performance in various types of sports in elite and recreational athletes [1–3], including sprint performance [4]. Besides sports performance, the ability to jump was shown to be a predictor for functional capacity [5] and the risk of falling [6]. Although there is evidence that muscle [7] or tendon stiffness [8] can be a predictor for sprint performance, there is not much evidence relating muscle or tendon stiffness to jump performance.

The most commonly used jump tests are the countermovement jump (CMJ), the squat jump (SQ), and the drop jump (DJ). All jump tests involve the participant being asked to jump as high as possible [9]; however, during a DJ, the participant should also have a contact time below 250 ms [10]. Therefore, a DJ is often associated with a fast stretch-shortening cycle (SSC), whereas it is a slow SSC for a CMJ [10].

Due to the high time pressure while performing a DJ, having stiffer tendons and/or muscles might be beneficial with regard to effective force transmission from the contractile element via the tendon to the bones [11,12]. Consequently, moderate positive correlations have been reported between gastrocnemius medialis muscle stiffness and jump height, as well as the reactive strength index (RSI = jump height/contact time), but not with contact time [12]. A further study reported that tendon stiffness is moderately related to contact time during a DJ [11]. However, Abdelsattar et al. [11] did not measure muscle stiffness, whereas Ando et al. [12] did not measure tendon stiffness. Hence, to obtain a clear picture of the relationships between tissue stiffness and DJ performance, there is a need to conduct a study which measures both muscle and tendon stiffness, especially of the calf muscles [13], and to relate this to DJ performance parameters.

When it comes to CMJs, the quadriceps muscles play a major role [13–15]. Bojsen-Møller et al. [16] showed a positive correlation between the stiffness of the musculotendinous structure of the vastus lateralis muscles and CMJ height (r = 0.55). There is also evidence that quadriceps power is significantly negatively related to muscle stiffness [17]. However, to date, there is no evidence linking muscle stiffness (of all muscles) and/or isolated tendon stiffness of the quadriceps muscle–tendon unit (MTU) with CMJ performance.

Therefore, the purpose of this study was to investigate the relationships between jump performance parameters and tissue stiffness (i.e., muscle stiffness, tendon stiffness) of the main muscles involved. According to previous studies, we hypothesized that DJ performance (i.e., ground contact time, RSI, jump height) will be related to Achilles tendon stiffness, gastrocnemius medialis stiffness, and gastrocnemius lateralis stiffness. Moreover, we assumed a relationship between CMJ performance (i.e., jump height, squat depth, RSI modified) to patellar tendon stiffness, rectus femoris stiffness, vastus medialis stiffness, and vastus lateralis stiffness.

2. Materials and Methods

2.1. Experimental Design

Each participant had to visit the laboratory on two separate days. The aim of the first visit was to familiarize the participant with the laboratory setup and the jumping technique. The participant performed approximately five–ten DJs and CMJs for training purposes until the investigator was convinced of the jumping technique of the participant. The actual test took place on the 2nd visit (5–7 days later than the 1st visit) and started with a 10 min warm-up routine on a stationary bike (Lode Corival, NL) at 60 rev·min^{-1} [18] and 90 W. Following the warm-up, the Myoton measurements were taken first, then the DJs were performed, and thirdly, the CMJs took place (see Figure 1). The order for the Myoton assessment was as follows: vastus medialis (VM), then vastus lateralis (VL), then rectus femoris (RF), then patellar tendon (PT), then gastrocnemius medialis (GM), then gastrocnemius lateralis (GL), and then Achilles tendon (AT).

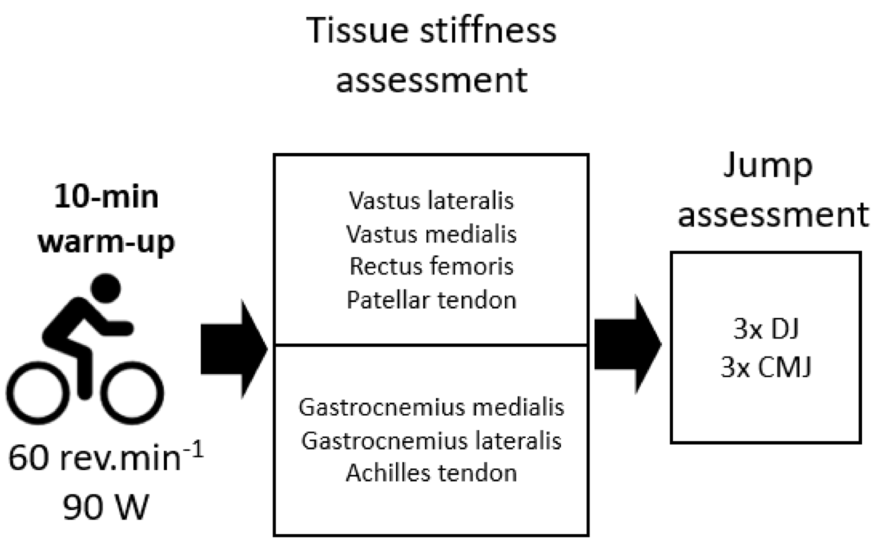

Figure 1. Schematic schedule of the study; CMJ—countermovement jump; DJ—drop jump.

2.2. Participants

A total of 16 males participated (age: 30.5 ± 4.5 years; weight: 82.3 ± 11.4 kg; height: 180.5 ± 6.3 cm) as volunteers in this study. All participants met the World Health Organization minimum activity guidelines [19] and hence, can be classified as recreationally active [20]. At the familiarization session, the investigator checked the participants' health status with various standardized questions. All participants confirmed that they had no current musculoskeletal pain or other orthopedic diseases in the lower extremity, as well as no other nonspecific musculoskeletal disorders (e.g., fibromyalgia). There was no history of surgery or other orthopedic injury in the back or lower extremities in the last twelve months and participants confirmed that there was no neurological disorder, no metabolic disorder, and they took no medication that affects perception or proprioception. Participants were asked not to perform any exhausting (i.e., intense or unusual) exercise 72 h prior to the tests. The participants were also informed about the test procedures and provided written content. The study was approved by the Ethics Commission of the Technical University of Munich (762/20 S-KH), and was performed in accordance with the Declaration of Helsinki.

2.3. Procedures

2.3.1. Myoton Measurements

A Myoton device (MyotonPRO, Myoton Ltd., Tallinn, Estonia) was used to assess the passive muscle and tendon stiffness of both the calf and anterior thigh MTUs. All the assessments were performed by one investigator experienced in human anatomy, with two months of training on the Myoton device especially. For the assessment of the triceps surae MTU (i.e., Achilles tendon, gastrocnemius medialis, and gastrocnemius lateralis), the participant was asked to remain in a resting position, lying prone, with their foot hanging freely off a physiotherapy bed [21]. For the anterior thigh muscles (vastus lateralis, vastus medialis, rectus femoris), the participant was asked to change into a supine position, with their hips and knees fully extended [22]. For the patellar tendon, the participant was asked to remain in a sitting position, with both hip and knee joints at 90° [22].

For the stiffness assessment, the probe of the Myoton device was applied perpendicular to the tissue, as proposed by the manufacturer. The measurement sites of the respective muscles were defined in accordance with SENIAM guidelines [23] for electrode placement during surface electromyography measurements. For the Achilles tendon, the assessment was at the level of the medial malleolus [24], and for the patellar tendon, it was at the midway point between the distal patellar rim and the tuberosity of the tibia [22].

In total, 3 consecutive mechanical impacts at 15 ms and a force of 0.3–0.4 N were applied from the Myoton device. Moreover, this was repeated two times, which resulted in nine impacts per muscle and tendon. Consequently, the muscle and tendon stiffness of every single mechanical impact was calculated as the force applied relative to the deformation of the tissue. The average value out of the three × three mechanical impacts was taken for the statistical analysis [25].

2.3.2. Jump Performance Assessment

Drop Jumps (DJs)

Each participant was asked to perform 3 DJs [26] (arms akimbo), from a 40 cm box onto a force plate (BP600900-2000, AMTI, Watertown, MA, USA), with maximum effort, i.e., keeping the ground contact time as short as possible [11]. The rest periods between jumps was 30 s, to avoid any fatigue [27]. The 40 cm box was placed on another force plate (BP600900-2000, AMTI, Watertown, MA, USA), which allowed us to monitor for possible vertical push-off from the box, which would increase the drop height. Jumps that did not appear to be maximal (i.e., compared with the familiarization session) and jumps with an identified push-off from the box had to be repeated. The DJ with the lowest ground contact time was used for the further analysis. Before moving to the CMJs, a 60 s break was given to the participants.

Countermovement Jumps (CMJs)

Each participant was asked to conduct three CMJs [26] on the same force plate as the DJ. The rest between the jumps was 30 s [27]. During the whole CMJ, the participant was asked to keep their hands placed on their hips [28]. The CMJ was performed by the participant lowering their center of mass by bending their knees to a self-selected grade.

Immediately after reaching the lowest position, the participant was asked to jump vertically, as high as possible. The CMJ with the highest jump height was used for the further analysis.

Jump Data Analysis

For the analysis of the CMJs and DJs, only the vertical ground reaction force was used. Data were captured (1000 Hz) using Nexus software (Oxford Metrics, Yarnton, Oxfordshire, UK). The final analysis was performed using a self-written MATLAB script (MATLAB R2021a, MathWorks Inc., Natick, MA, USA). Raw force data were smoothed using a 10 ms moving average.

For the DJs, the ground contact time represents the time the subject was in contact with the force plate, using a threshold of 10 N. Jump height was calculated using the flight time method (threshold landing 10 N), and finally the ratio between the DJ height and contact time represents the RSI.

For the CMJs, the jump height was calculated using the impulse–momentum method. In addition, the modified RSI was calculated by forming the ratio between the CMJ height and the time the subject needed for the CMJ until take-off. The beginning of the CMJ and the start of the flight phase (take-off) were defined using a threshold of 10 N deviation from baseline. The center of mass (CoM) displacement until the deepest squat position was defined as the difference between upright standing (0 cm displacement) and the local minimum between the beginning of the CMJ and the take-off. The CoM displacement-time curve was calculated by double integration (MATLAB trapz function) of the acceleration–time curve.

2.4. Statistical Analysis

SPSS (version 27.0, SPSS Inc., Chicago, IL, USA) was used for all the statistical analyses. Since all the data were normally distributed (assessed with the Shapiro–Wilk test), a Pearson's correlation (rP) analysis was used to calculate the relationship between the variables. The alpha level was set to 0.05. The effect sizes of rP were established following the suggestions of Hopkins [29]. Thus, the value of the effect size was the same as the correlation. Effect sizes of 0–0.1, 0.1–0.3, 0.3–0.5, 0.5–0.7, 0.7–0.9, and 0.9–1.0 were defined as trivial, small, moderate, large, very large, and nearly perfect–perfect, respectively.

3. Results

The raw data of this manuscript is provided at the following link: https://doi.org/10.6084/m9.figshare.18297692.v1.

Mean values and standard deviations of all parameters are presented in Table 1.

Table 1. Mean and standard deviation (SD) of the assessed parameters.

Parameter	Mean ± SD
Patellar tendon stiffness (N/m)	838.7 ± 109.9
Vastus lateralis stiffness (N/m)	296.4 ± 25.2
Vastus medialis stiffness (N/m)	251.4 ± 27.1
Rectus femoris Stiffness (N/m)	250.3 ± 33.4
Achilles tendon stiffness (N/m)	808.2 ± 67.4
Gastrocnemius medialis stiffness (N/m)	312.7 ± 43.2
Gastrocnemius lateralis stiffness (N/m)	334.9 ± 44.5
CMJ jump height (m)	0.36 ± 0.06
CMJ squat depth (m)	−0.35 ± 0.06
CMJ reactive strength index	0.46 ± 0.11
DJ jump height (m)	0.21 ± 0.06
DJ contact time (s)	0.20 ± 0.03
DJ reactive strength index	1.09 ± 0.36

The correlation analysis between the DJ performance parameters (contact time, jump height, RSI) and Achilles tendon stiffness and muscle stiffness of both gastrocnemii showed no significant association, ranging from trivial to small effect sizes (from −0.07 to 0.24) (see Table 2).

Table 2. Pearson's correlation(=rP) between drop jump (DJ) performance values (CT—ground contact; RSI—reactive strength index; JH—jump height) and the stiffness of the gastrocnemius medialis (GM), gastrocnemius lateralis (GL), and Achilles tendon (AT). The correlation is in bold; CI—confidence interval; ES—effect size.

	rP	CI 95 %	*p*	ES
GM—DJ_CT	**0.24**	(−0.29–0.66)	0.38	0.24
GM—DJ_RSI	**0.02**	(−0.48–0.51)	0.94	0.02
GM—DJ_JH	**0.13**	(−0.39–0.59)	0.62	0.13
GL—DJ_CT	**0.16**	(−0.37–0.61)	0.56	0.16
GL—DJ_RSI	**0.02**	(−0.48–0.51)	0.93	0.02
GL—DJ_JH	**0.08**	(−0.43–0.56)	0.76	0.08
AT—DJ_CT	**−0.07**	(−0.54–0.44)	0.81	−0.07
AT—DJ_RSI	**0.11**	(−0.41–0.57)	0.70	0.11
AT—DJ_JH	**0.09**	(−0.42–0.56)	0.73	0.09

The correlation analysis between the CMJ performance parameters (jump height, squat depth, RSI) and patellar tendon or vastus medialis stiffness, vastus lateralis stiffness, and rectus femoris stiffness showed no significant association, ranging from small to moderate effect sizes (from −0.13 to 0.36) (see Table 3).

Table 3. Pearson's correlation (=rP) between countermovement jump (CMJ) performance values (JH—jump height; SD—squat depth; RSImod—reactive strength index modified) and the stiffness of the patellar tendon (PT), vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF). The correlation is in bold; CI—confidence interval; ES—effect size.

	rP	CI 95%	*p*	ES
PT—CMJ_JH	**−0.03**	(−0.52–0.48)	0.92	−0.03
PT—CMJ_SD	**0.36**	(−0.17–0.72)	0.18	0.36
PT—CMJ_RSImod	**−0.04**	(−0.52–0.47)	0.90	−0.04
VL—CMJ_JH	**−0.02**	(−0.51–0.48)	0.95	−0.02
VL—CMJ_SD	**−0.19**	(−0.63–0.34)	0.48	−0.19
VL—CMJ_RSImod	**−0.13**	(−0.59–0.39)	0.64	−0.13
VM—CMJ_JH	**0.15**	(−0.37–0.60)	0.57	0.15
VM—CMJ_SD	**0.05**	(−0.46–0.53)	0.85	0.05
VM—CMJ_RSImod	**0.15**	(−0.37–0.60)	0.58	0.15
RF—CMJ_JH	**0.22**	(−0.31–0.65)	0.41	0.22
RF—CMJ_SD	**−0.01**	(−0.50–0.49)	0.98	−0.01
RF—CMJ_RSImod	**−0.02**	(−0.51–0.48)	0.94	−0.02

4. Discussion

The purpose of this study was to relate tissue stiffness (i.e., muscle stiffness or tendon stiffness) with DJ and CMJ performance. We hypothesized that DJ performance would be related to Achilles tendon stiffness, gastrocnemius medialis stiffness, and gastrocnemius lateralis stiffness. Moreover, we assumed a relationship between CMJ performance to patellar tendon stiffness, rectus femoris stiffness, vastus medialis stiffness, and vastus lateralis stiffness. Against our hypotheses, the correlation analysis showed no significant association between DJ performance parameters (contact time, jump height, RSI) and Achilles tendon stiffness or muscle stiffness of both gastrocnemii. Similarly, there was no significant association between CMJ performance parameters and patellar tendon stiffness, rectus femoris stiffness, vastus medialis stiffness, or vastus lateralis stiffness.

A previous study [12] reported a positive moderate relationship between gastrocnemius medialis stiffness and some (jump height and RSI) but not all (contact time) DJ parameters. However, no such correlation was seen in the soleus muscle. The authors assumed that this discrepancy can be likely explained by the different slack angles between the gastrocnemius medialis and soleus muscles [12,30]. Furthermore, another study reported a moderate positive relationship between tendon stiffness and ground contact time during a DJ [11]. Bringing the findings of Abdelsattar et al. [11] and Ando et al. [12] together, there seems to be evidence that, overall, a stiffer MTU might be favorable for DJ performance. However, the current study did not support these findings.

In the current study, great emphasis was given to familiarizing the participants with a suitable DJ technique in a separate familiarization session. In general, we were aiming to train the participants to keep the ground contact time at ≤250 ms, as suggested by Schmidtbleicher et al. [10], for a reactive DJ. Although Ando et al. [12] also familiarized their subjects, there were differences when comparing the studies of Ando et al. [12], Abdelasattar et al. [11], and the current study. While a relatively short contact time during the DJ was seen in the participants in the current study (from 133 ms to 225 ms), in the studies of Ando et al. [12] and Abdelsattar et al. [11], the participants' ground contact time during the DJ ranged from 148 ms to 290 ms and from 150 ms to 350 ms, respectively. Therefore, one could assume that the participants in the current study might be better conditioned to the DJ, which likely resulted in a better (i.e., more economical) DJ technique. Hence, it could be assumed that the participants in the current study did not necessarily need such stiffness in either the muscle or tendon to perform a proper DJ, as seen in previous studies [11,12]. Consequently, future studies should investigate the relationship between tissue stiffness (i.e., muscle stiffness and tendon stiffness) and DJ performance in participants that are familiarized with DJs, and in participants that are not familiarized with DJs.

Moreover, as suggested by Maffiuletti et al. [31], the sample in the current study might have been too homogeneous in both stiffness values and jump performance values to find a significant correlation between these variables. This is underlined by, e.g., the smaller range of contact times assessed in the current study (92 ms), compared with the studies of Ando et al. [12] and Abdelsatter et al. [11], with 142 ms and 200 ms, respectively.

A further possible explanation for the contradictory findings between the previous studies [11,12] and the current study might be in the different methods used to assess tissue stiffness. Ando et al. [12] used shear wave elastography to assess muscle stiffness and Abdelassattar et al. [11] used force elongation curves to assess tendon stiffness. The technique used in the current study was myotonometry, by the use of a Myoton device. Excellent reliability (i.e., ICC > 0.75; [32]) of the muscle and tendon stiffness assessment with the Myoton device has been reported in previous studies which assessed the reliability in these MTUs (quads: [33,34]; calf: [24,34]). Moreover, the validity of the Myoton device was also confirmed by a previous study [24]. Good correlation between shear wave elastography and the Myoton device has also been reported recently [34]. Hence, it can be assumed that the Myoton device is valid, reliable, and will likely result in the same outcome as the outcome obtained with other techniques, such as ultrasonic shear wave elastography.

With regard to CMJ performance, we did not find any significant correlation with patellar tendon stiffness or rectus femoris, vastus medialis, or vastus lateralis stiffness. However, Bojsen-Møller et al. [16] reported a large positive correlation (r = 0.55) between the stiffness of the musculotendinous structure of the vastus lateralis muscles and CMJ height in 16 highly trained athletes. Again, the different findings in the study by Bojsen-Møller et al. [16] and the current study might be explained by the different methods used for the stiffness assessment (active force elongation curves via dynamometry and ultrasound vs. passive Myoton measurements) and/or by the different populations (well-trained vs. moderately active) investigated. Consequently, it is likely that variables other than muscle or tendon stiffness of the quadriceps MTU are related to CMJ performance. For example, Vanezis and Lees [35] reported that strength and the rate of force development are predictors for good CMJ performance, irrespective of the technique used (i.e., starting position). Moreover, the strength of the leg muscles has been found to be a determinant parameter for vertical jump height in some [14,36] but not all studies [37]. In addition, a further study reported that strength of the knee extensors is only related to vertical jump height when it is relative to body mass [26,38]. When quadriceps strength is related to muscle stiffness of the rectus femoris, no association has been reported [17]. However, these authors reported that rectus femoris muscle stiffness was significantly negatively related to power [17]. This would indicate that a more compliant muscle can lead to higher power outcomes. Besides strength and power, a further possible predictor for CMJ jump performance has been found in flexibility of the quadriceps muscle, although this relationship was only to a moderate extent [26].

This study has some limitations. We did not control for the knee angle position at the start of the concentric phase of the CMJ. A smaller squad depth might change the performance of the SSC due to a change of the muscle–tendon unit [13]. Hence, a deeper position might result in in bigger jump height due to an increase in, e.g., storage and release of elastic energy. However, in the work of Gheller et al. [39] it was shown that the self-selected knee flexion angle resulted in the same jumping heights compared to a bigger knee flexion angle (>90°), and outperformed a knee flexion angle (<90°) smaller than the preferred position. A reason might be that acute changes in the squad position, prior to the concentric phase, might affect the intersegmental coordination and, therefore, beneficial effects might be diminished [39]. Taken together, the authors assume that a self-selected initial start position did not influence the results of the study. Another limitation is the generalizability of the results. Our subjects reflected a recreationally trained cohort; therefore, results cannot be transferred to elite or highly trained athletes. Previous studies have reported that elite or highly trained athletes have another muscle–tendon structure (e.g., stiffness [8]) as well as function (e.g., strength [40]) compared with the recreational trained or non-athletes.

In summary, the data obtained in the current study showed no significant association between muscle and tendon stiffness of the respective muscles and DJ or CMJ performance variables. Therefore, it is likely that other variables, such as jump technique, body weight, or strength, play a more important role in DJ and CMJ performance. Hence, future studies should investigate such potential relationships. This would help to draw a clearer picture and to give training recommendations to improve jump performance.

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