

# Influence of lower-limb muscular and tendon mechanical properties and strength on countermovement jump performance

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**Title:**

Influence of lower-limb muscular and tendon mechanical properties and strength on countermovement jump performance

**Running title:**

Strength and lower-limb mechanics on CMJ

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## **Abstract**

**BACKGROUND:** The aim of the study is to examine the relationship between measures of muscle and tendon mechanical properties and strength on countermovement jump (CMJ) performance. **METHODS:** Twenty-six physically active participants (males; n = 16; females; n = 10) were tested. Testing comprised of measuring the mechanical properties of lower limb muscles and tendons using myotonometry, isometric and isokinetic knee extensor strength through dynamometry, and CMJ's with a force platform. **RESULTS:** Large positive correlations were observed between CMJ jump height and Achilles tendon stiffness (N/m) ( $r=0.56$ ) and Achilles tendon tone (Hz) ( $r=0.553$ ). Large negative correlations were found between CMJ height and Achilles tendon elasticity ( $r=-0.658$ ), and Achilles tendon relaxation ( $r=-0.572$ ), and Achilles tendon creep ( $r=-0.589$ ). Large correlations ( $r=0.592$  to  $0.659$ ) were observed between CMJ height and all measures of isometric and isokinetic dynamometry measures. Achilles tendon stiffness, elasticity level and relaxation, and isokinetic peak concentric torque (N.m) explained 63% of this variance. **CONCLUSIONS:** Greater stiffness of the Achilles tendon may improve CMJ performance due to the improved transfer of concentric and eccentric force of the knee extensor muscles. Practitioners need to implement specific interventions to target increasing Achilles tendon stiffness to improve countermovement jump performance.

## **Keywords**

ACHILLES TENDON - LOWER EXTREMITY – MUSCLES - PLYOMETRIC EXERCISE  
- MUSCLE STRENGTH

## Introduction

Successful performance of quick movements such as sprints and jumps are essential in many sports. The assessment of a countermovement jump (CMJ) is an inexpensive, easy to administer, and commonly used method of assessing explosive power (1). Therefore, CMJ is one of the most widely used tests for monitoring neuromuscular status in team sports (2), the individual (3), as well as for selection (4) and talent identification (5). The CMJ is complex motor skill that requires force production and the ability to transfer these forces throughout the entire the kinetic chain (6). Therefore, understanding the determinants of CMJ performance is important for the athlete and the practitioner.

The CMJ can be affected by several parameters such as kinematics and kinetics (7), and strength (8). However, the influence of muscle or tendon mechanical properties has had limited attention in relation to CMJ performance. Myotonometry has been shown to be a quick and reliable tool for assessing the viscoelastic properties of muscles and tendons (9; 10; 11). Muscle stiffness is defined as the resistance of soft tissue to deformation or change in length (12). High levels of muscle stiffness have been suggested as beneficial for actions that rely on the stretch shorten cycle (SSC) such as jumping or the CMJ (12). Muscular mechanical stiffness may influence CMJ performance due to the greater capacity of the compliant structure (muscle or tendon) to absorb and re-use rapidly greater amounts of elastic energy for a given force (13). In previous myotonometry based studies of movements that involved lower limb SSC actions, muscle stiffness was positively associated with greater serve velocity in tennis (14) and tendon stiffness was affected by regular badminton practice (15). However, to date no studies have scrutinised the relationship between myotonometry derived measures of muscle and tendon mechanical properties and CMJ performance. Understanding the relationship between muscle and tendon mechanical function through myotonometry and CMJ performance can provide practitioners with the ability to prescribe specific strength and conditioning programs quickly

that focus on specific structural adaptations rather than merely mimicking velocities and movement patterns. Therefore, the aim of the study is to examine the relationship between measures of muscle and tendon mechanical properties, and strength on CMJ performance. We hypothesised that a strong positive association will exist between measures of strength and muscular stiffness with CMJ jump height.

### **Materials and Methods**

Participants: Twenty six recreationally active adults (males;  $n = 16$ , age;  $24.8 \pm 5.0$  years, height;  $178.2 \pm 5.6$  cm, mass;  $77.8 \pm 13.2$  kg, females;  $n = 10$ , age;  $21.0 \pm 1.6$  years, height;  $167 \pm 5.3$  cm, mass;  $61.3 \pm 8.9$  kg) volunteered to take part in this study. All participants self-reported as being recreationally active (IPAQ; males;  $4.4 \pm 2.0$  hrs $\cdot$ wk $^{-1}$ , females;  $2.3 \pm 1.6$  hrs $\cdot$ wk $^{-1}$ ) and had no recent history ( $> 3$  months) of resistance or plyometric exercise training. All of the participants were injury free and had not reported to suffering from any musculoskeletal injury in the previous 6 months. All participants initially completed a health screen questionnaire to assess eligibility for the study. Participants were fully aware of the procedures and potential risks involved in the experiment, and provided written, informed consent prior to data collection. The experimental procedures were carried out in accordance with the standards outlined in the declaration of Helsinki (1964) and the study received approval by the institutional ethics committee (ID: P109131).

Protocol: Participants avoided strenuous exercise in the 48 h prior to the experiment. Participants were familiar to the criterion measures and completed a 5 minute warm-up on a mechanically braked cycle ergometer (Monark, 824E, Ergomedic, Sweden), at a cadence of 70 rev $\cdot$ min $^{-1}$ . The participants completed the criterion tests in the following order: myotonometry, Warm-up, countermovement jump and isokinetic dynamometry.

Muscular mechanical properties: A hand-held myotonometer (Myoton-Pro, Myoton AS, Tallinn, Estonia) measured muscle mechanical properties of the vastus lateralis muscle (VL), gastrocnemius lateralis muscle (GL) and Achilles tendon (AT). The methods of Hill, Rosicka and Wdowski (9) were followed where all measurements were made on the right side and to maintain consistency between participants, assessment points were drawn with a marker and measured by one operator. All outcomes on the posterior aspect of the lower limbs were obtained with the participant lying in a prone position, with feet hanging off the table at an ankle angle of 90°. For anterior aspect measurement, the participant was lying supine with the hip and knee extended. The measurement site for VL was at 50% of the straight-line distance between the greater trochanter and fibulae capitulum. Muscle mechanical properties of GL were measured at 30% of the distance between fibulae capitulum and Achilles tendon insertion (16), at the central part of muscle belly. AT was measured 2 cm proximal to the superior aspect of the calcaneus (17). The standard flat end probe (3mm diameter) of the Myoton-Pro was placed perpendicular to the surface of the skin at all measurement sites and the device delivers a short mechanical impulse to the skin and below the tissues, directly under the probe (duration: 15 ms; force: 0.3 – 0.4 N). This generates natural oscillations within the muscle. The device records and calculates muscle mechanical properties within a few seconds after measurement. A multi scan (five single measurements) was taken with the MyotonPRO, with a further three repetitions of multi scan measurements on each tested muscle and tendon. We recorded the tone (Oscillation frequency Hz), dynamic stiffness (N/m), elasticity (Arbitrary unit), relaxation time (ms) and creep (Deborah number) from the MyotonPRO outputs and used the average over the three repetitions in subsequent analysis (18).

Counter movement jump: Participants then performed three counter movement vertical jump (CMJ) trials. In the eccentric phase, the centre of mass is lowered by flexing the hips, knees, and ankles (dorsiflexion). The concentric phase begins when the descent of the centre of mass

stops, generally at maximum knee flexion. From the crouched position, extension of the hips, knees, and plantar flexion of the ankles propels the body upward until the feet leave the ground (take-off). The participants stood with both feet on a 0.35×0.35 m force platform (PASPORT Force Platform, PS-2141, Bilston, UK, 1000 Hz). Each trial began with the participant standing still. An investigator in sight of the participant gave the prompt to jump and the participant performed a maximum-effort CMJ, with their hands placed on their iliac crest. A successful trial was classified as the participant standing stationary with both feet on the floor, jumping straight up, and landing on both feet without taking any steps. Participants were instructed to leave the force platform with the knees and ankles extended and land in a similarly extended position. The jump height was calculated from the time in air (19) and key CMJ kinetic variables were calculated using the method of Chavda et al. (20), that included peak and average concentric force, expressed in Newton's (N) and relative to body weight (BW). We used the average of the three trials in subsequent analyses.

Muscular Strength: Finally, isokinetic dynamometry (KinCom 125AP; Chattanooga Group, Chattanooga, TN) was used to determine the dynamic strength of the right limb knee extensor muscle torque and force. The dynamometer was calibrated according to the manufacturer's instructions before the testing. The participants were seated with hip flexed at an angle of 90° with the back of the knee joint was on the edge of the seat with a knee flexion angle of 90° from anatomical zero (0°) (21). The distal shin pad of the dynamometer was attached 4–5 cm proximal to the medial malleolus, two seatbelts were applied across the chest and pelvis, while straps were applied to the mid-thigh to reduce movement during contractions. The dynamometer rotational axis was aligned with the lateral femoral condyle of the dominant knee (knee joint axis of rotation). Three x five-second maximal isometric concentric knee extensions repetitions were performed, with 2 minutes rest between repetitions, with the knee at a flexion angle of 90° from anatomical zero (0°). Next, a set of 3 consecutive repetitions of maximal

knee concentric/eccentric extension through 90°, at a contraction velocity of 60°/sec. Participants were given strong verbal encouragement throughout both trials. The participant had to maintain a minimum force of 20 N against the resistance pad for the exercise to continue. Peak force (N) and torque (N.m) were recorded for each repetition. Peak torque (N.m) was calculated by multiplying the force by the lever arm radius. The largest peak values of the three trials were used in subsequent analyses.

Statistical analyses: The results presented are expressed as mean  $\pm$  SD and 95% confidence intervals (95% CI). The normality of the distributions and homogeneity of variances were assessed with the Shapiro–Wilk test. All variables showed normal distributions except for AT Elasticity. To give an indication of the reliability of test measurements of isometric muscle torque and stiffness were assessed using intraclass correlation coefficients (ICCs) and the coefficient of variation (CV) between the second and third trials. We found high intra-class correlation coefficients and low coefficients of variation for isometric muscle torque (ICC: 0.99, CV: 2.7 %). We also found high intra-class correlation coefficients and low coefficients of variation for stiffness (ICC: 0.97 – 0.99, CV: 1.38 – 1.89%), for all measurement sites. We utilised Pearson correlation coefficients to examine the relationships between jump height, CMJ kinetic variables, muscle strength, and muscular mechanical properties variables. AT elasticity was correlated with the CMJ jump height using Spearman Rho correlation. Correlations were classified as trivial (0–0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), nearly perfect (0.9), and perfect (1.0) (22). Statistical significance was accepted at an alpha level of  $p \leq 0.05$ . A multiple linear regression was conducted to observe if muscle mechanical properties, muscular strength and CMJ kinetic variables predicted the jump height of the participant. All statistical analyses were performed using Jeffreys’s Amazing Statistics Program 0.14 (JASP TEAM 2020. Amsterdam, Netherlands).

## **Results**



The correlations between muscle mechanical properties and jump height are presented in Table 1. Large positive correlations were observed between CMJ jump height and AT Stiffness (N/m) (Figure 1.) ( $r=0.56$ ;  $p=0.003$ ;  $CI=0.22,0.778$ ) and AT Tone (Hz) ( $r=0.553$ ;  $p=0.003$ ;  $CI=0.21,0.774$ ). Large negative correlations were found between CMJ jump height and AT Elasticity ( $r=-0.658$ ;  $p<.001$ ;  $CI=-0.833,-0.363$ ), and AT Relaxation ( $r=-0.572$ ;  $p=0.002$ ;  $CI=-0.723,-0.095$ ), and AT Creep ( $r=-0.589$ ;  $p=0.002$ ;  $CI=-0.795,-0.261$ ) (Figure 1.).

Correlations between muscular strength, CMJ kinetic variables and CMJ jump height are presented in Table 1. Large correlations were observed between CMJ jump height and all muscular strength variables ( $r=0.592 - 0.659$ ;  $p=0.001 - <0.001$ ;  $CI=0.265,0.833$ ) (Figure 2.). No CMJ kinetic variables were correlated with CMJ jump height ( $p>0.05$ ).

Using the enter method it was found that AT stiffness (N/m), AT elasticity level, AT relaxation, and isokinetic peak concentric torque (N.m) explain a significant amount of the variance in the CMJ jump height ( $F(4, 21) = 9.108$ ,  $p < .001$ ,  $R^2 = .634$ ,  $R^2$  Adjusted = .565). The analysis showed that AT elasticity can predict CMJ jump height ( $p=0.009$ ). Participants jump height is equal to  $2.442 + 0.0003947$  (isokinetic peak concentric torque N.m)  $- 0.001$  (AT stiffness N/m)  $- 0.179$  (AT elasticity)  $- 0.151$  (AT relaxation).

## Discussion

The aim of the study was to examine the relationship between measures of lower-limb muscle and tendon mechanical properties, and strength on CMJ performance. We are the first study to utilise the combined methods of myotonometry, and dynamometry to investigate the relationship between mechanical properties, and strength of the lower limbs with CMJ performance. These results indicate that those who wish to ensure the appropriate transfer of force from the quadriceps to the ground should potentially target the mechanical properties of the AT in their training.

We found that every mechanical property measured of the AT was statistically correlated with CMJ height, with a greater AT stiffness and tone correlated with a greater CMJ height. This is the first study to use myotonometry derived measures of muscle and tendon stiffness in relation to the CMJ, previous literature using Ultrasound derived measures of stiffness have observed similar positive correlations between Achilles tendon stiffness and CMJ height (23). Stiffer tendons have been suggested to allow faster tension changes, joint motion responses (24) and faster transfer of force to the bones when compared to a compliant tendon (25). Furthermore, the tone (i.e. intrinsic tension) of the tendon in the resting state suggest a positive correlation with CMJ height. Ours is the first study to examine the resting tension of the AT in relation to CMJ height but two previous studies have observed greater tone of the patella tendon (15) and of the rectus femoris (26) as people aged. Larger tone of the Achilles tendon in a participant when compared to another is likely a consequence of a greater tendon stiffness and contributes to the successful application of the SSC as it is understood that the tendons act as a spring (27). Our results provide novel data derived from a hand held myotonometer to further support the importance of the mechanical properties of the Achilles tendon for CMJ performance. Future research to determine whether training can influence mechanical properties of the Achilles tendon and subsequent CMJ performance is warranted.

We found that concentric muscular force is positively correlated with CMJ height. We further observed that isokinetic peak concentric torque (N.m) was one of the key predictor variables of CMJ height in the regression model. The relationship between muscular strength and CMJ height has been widely observed in the literature (28). Larger muscular force production during the concentric contraction of the quadriceps would enable a greater angular velocity of extension around the knee joint and larger joint power, which has been previously identified as a significant contributor to CMJ height (7). It has been established that individuals with higher maximum muscle strength commonly also feature higher tendon stiffness to be

able to tolerate the mechanical loading placing upon the tendon by the working muscle (29). When related to CMJ performance, our study provides novel information by suggesting in the same study that the larger muscle force generated by the muscles is more effectively transferred through a stiffer AT. The development of stronger muscles capable of more powerful joint movements and stiffer tendons is therefore important to CMJ performance and practitioners should focus on interventions that can cause these adaptations. We investigated the Achilles tendon but the viscoelastic properties of other tendons of the lower limbs may also be a contributing factor to CMJ height. Future research is required into the myotonometry based measurements of the properties of tendons not explored in the current study.

We have highlighted in the study that the mechanical properties of the Achilles tendon as measured by myotonometry are strong predictors of CMJ height but this was not observed for the mechanical properties of the VL and GL. There is limited research on the mechanical properties of muscles utilising a myotonometer procedure and the relationship with CMJ or dynamic movement performance. A study by Chang et al. (30) suggested that amateur basketball players exhibit significantly higher stiffness values in the gastrocnemius muscle group than a non-athletic control group and from a biomechanical perspective, stiffer muscles may use tendon elasticity more efficiently (31). Although no relationship to performance was investigated, a study has suggested that stiffness of the gastrocnemius muscle group does not change after a 6-week plyometric training intervention but that the stiffness increases in the tibialis anterior muscle group (32). Therefore, the mechanical properties of the gastrocnemius muscle group may not be as influential to CMJ performance as other muscle groups. A further explanation for non-significant correlations between the mechanical properties of the VL and GL could be the motor skill challenge of performing a CMJ. A greater stiffness of soft tissue simultaneously increases the force required to produce a change in its length. As complex motor skills rely on the principle of coordination of individual impulses and an effective kinetic

chain (6), high levels of muscle stiffness could be counterproductive by affecting execution for these particular actions (14). Our population of recreationally active adults, although familiar with the CMJ, may have not appropriately developed the coordination pattern to effectively utilise muscle stiffness in the VL and GL during the CMJ. Further research is needed to understand the role muscle stiffness has on the coordination of complex motor skills.

While this is the first study to investigate the relationship between mechanical properties of the lower limbs with CMJ performance measured using combined methods of dynamometry, and myotonometry, some limitations should be addressed in future studies. Firstly we only measured the strength of the knee extensors. The flexors have also been previously suggested to contribute to CMJ height (33) and would provide valuable information concerning the lowering phase of the CMJ. Secondly, we investigated the GL, AT and VL and our results suggest that investigating tendons around the knee joint and the muscles that control dorsiflexion may provide further understanding of the contribution of the lower limb mechanical properties for CMJ height. Finally, further use of a quick and non-invasive myotonometry device for the assessment of longitudinal investigations into the adaptation of mechanical properties of soft tissues are required.

### **Conclusions**

Our study potentially demonstrates that greater AT stiffness and tension is a strong predictor of CMJ performance, possibly enabling the greater transfer of concentric and eccentric force of the knee extensor muscles. Furthermore, the vastus lateralis and gastrocnemius lateralis muscle mechanics did not correlate with countermovement jump height. Myotonometry provided quick and reliable measures of the mechanical properties of tendons and muscles. These findings suggest that future interventions that specifically target increasing AT stiffness and resting tension may improve countermovement jump performance.

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## Authors Contributions

All authors read and approved the final version of the manuscript and were involved with the conception of the study, the data collection, data analysis and review of the manuscript.

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Table 1. Pearson's correlation coefficients (r) between muscle mechanical properties, muscle strength, CMJ kinetics and jump height (n = 26).

	<b>Mean±SD</b>	<b>r</b>	<b>p</b>	<b>95% CI</b>
<b>Jump Height</b>	0.31±0.06	-	-	-
<b>GM Stiffness (N/m)</b>	312.9±59.6	0.233	0.251	-0.169,0.569
<b>GM Tone (Hz)</b>	17.4±2.4	0.337	0.092	-0.057,0.641
<b>GM Elasticity</b>	1.05±0.20	-0.039	0.849	-0.42,0.354
<b>GM Relaxation</b>	17.6±3.4	-0.273	0.177	-0.597,0.128
<b>GM Creep</b>	1.08±0.20	-0.241	0.235	-0.575,0.161
<b>VL Stiffness (N/m)</b>	311.9±41.9	-0.138	0.500	-0.499,0.263
<b>VL Tone (Hz)</b>	16.6±2.1	-0.003	0.989	-0.39,0.385
<b>VL Elasticity</b>	1.59±0.25	0.164	0.424	-0.239,0.518
<b>VL Relaxation</b>	18.3±2.4	0.236	0.245	-0.166,0.571
<b>VL Creep</b>	1.14±0.14	0.286	0.156	-0.114,0.606
<b>AT Stiffness (N/m)</b>	779.6±74.4	0.56	<b>0.003*</b>	0.22,0.778
<b>AT Tone (Hz)</b>	31.0±2.2	0.553	<b>0.003*</b>	0.21,0.774
<b>AT Elasticity</b>	0.93±0.23	-0.658	<b>&lt; .001*</b>	-0.833,-0.363
<b>AT Relaxation</b>	6.6±0.6	-0.572	<b>0.002*</b>	-0.723,-0.237
<b>AT Creep</b>	0.44±0.04	-0.589	<b>0.002*</b>	-0.795,-0.261
<b>Isometric Peak Force (N)</b>	770.7±231.8	0.623	<b>&lt; .001*</b>	0.311,0.814
<b>Isometric Peak Torque (N.m)</b>	223.5±67.2	0.623	<b>&lt; .001*</b>	0.311,0.814
<b>Isokinetic Peak Concentric Force (N)</b>	542.8±173.3	0.659	<b>&lt; .001*</b>	0.365,0.833
<b>Isokinetic Peak Concentric Torque (N.m)</b>	157.4±50.3	0.659	<b>&lt; .001*</b>	0.365,0.833
<b>Isokinetic Peak Eccentric Force (N)</b>	688.7±241.2	0.592	<b>0.001*</b>	0.265,0.797
<b>Isokinetic Peak Eccentric Torque (N.m)</b>	199.7±70.0	0.592	<b>0.001*</b>	0.265,0.797
<b>CMJ Peak Concentric Force (N)</b>	1212.9±232.9	0.226	0.266	-0.176,0.564
<b>CMJ Peak Concentric Force (BW)</b>	1.74±0.20	-0.131	0.523	-0.493,0.27
<b>CMJ Peak Eccentric Force (N)</b>	964.1±187.8	0.21	0.302	-0.193,0.553
<b>CMJ Peak Eccentric Force (BW)</b>	1.38±0.15	-0.163	0.427	-0.518,0.24

\*Significant correlation p<0.05

## **Titles of Figures**



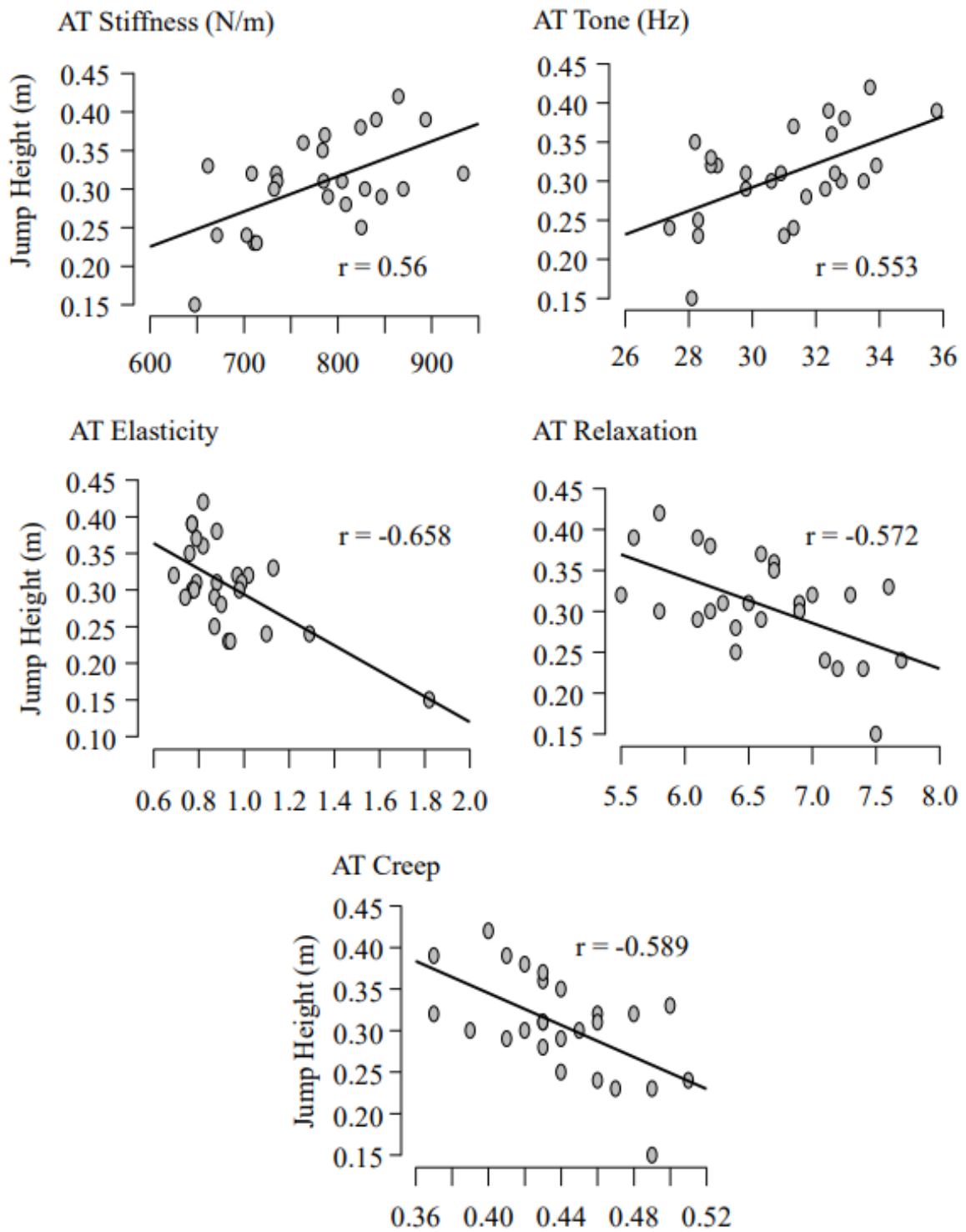


Figure 1. Pearson's correlation coefficients ( $r$ ) between measures of AT mechanical properties and jump height ( $n = 26$ ).

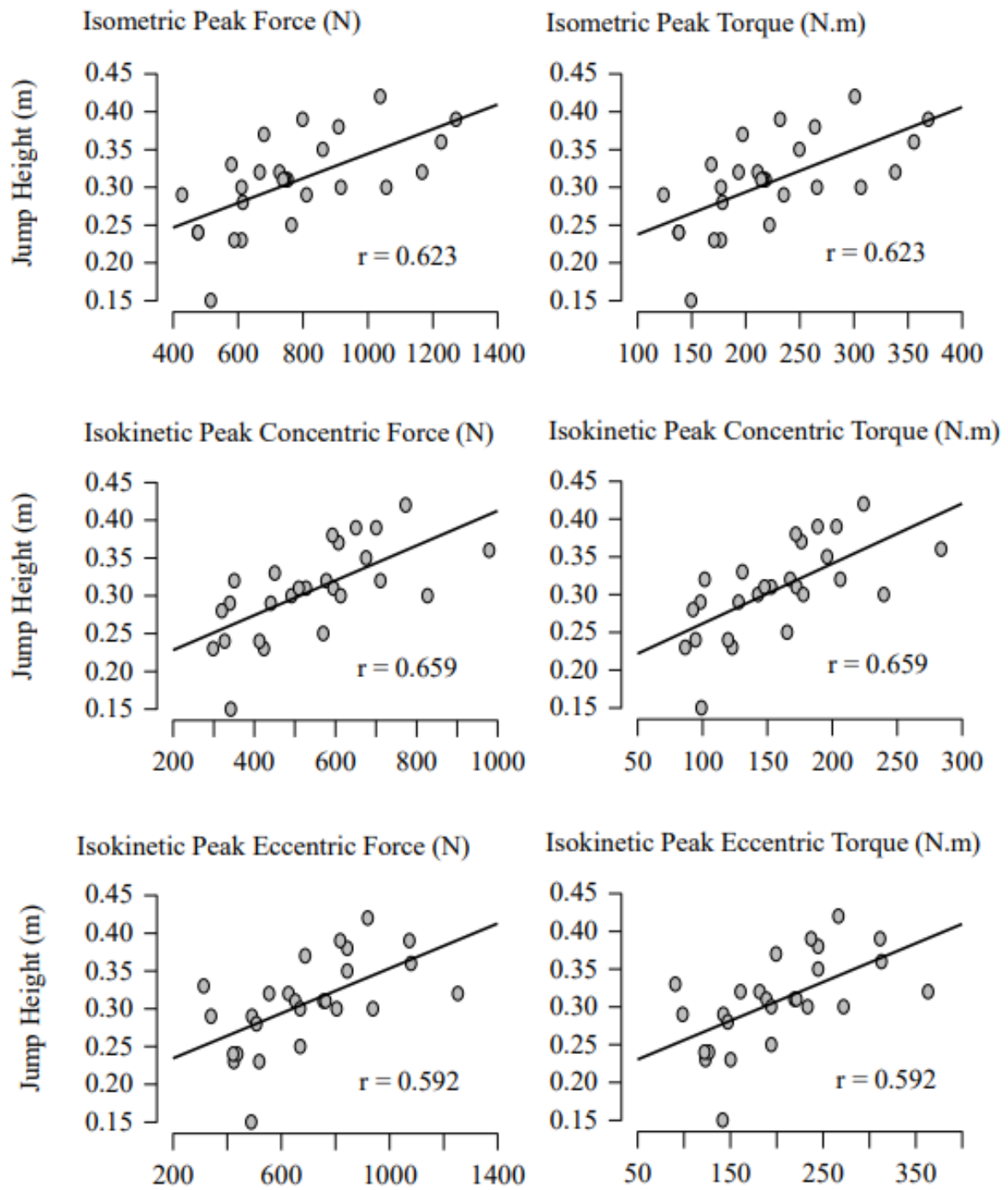


Figure 2. Pearson's correlation coefficients ( $r$ ) between measures of muscle strength and jump height ( $n = 26$ ).