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**Research article**

# Joint Coordination and Muscle-Tendon Interaction Differ Depending on The Level of Jumping Performance

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## Abstract

The countermovement jump is a popular measurement modality to evaluate muscle power in sports and exercise. Muscle power is essential to achieve a high jump, yet the well-coordinated movement of the body segments, which optimizes the stretch-shortening cycle (SSC) effects, is also required. Among the proposed explanations of SSC effects, this study investigated whether the ankle joint kinematics, kinetics, and muscle-tendon interaction depend on the level of jump skill and the jump task. Sixteen healthy males were grouped as a function of their jump height (High jumpers; greater than 50 cm, Low jumpers; less than 50 cm). They were instructed to jump with two intensities; light effort (20 % of their height) and maximal effort. Joint kinematics and kinetics of the lower limbs were analyzed using a 3-dimensional motion analysis system. The muscle-tendon interaction was investigated using B-mode real-time ultrasonography. As the jump intensity increased, all participants jumped with increased joint velocity and power. However, the high jumper shows less fascicle shortening velocity (-0.2 ± 0.1 m/s) than the low jumper group (-0.3 ± 0.1 m/s) and greater tendon velocity, which indicated the capability of elastic energy recoil. In addition, the delayed onset time of ankle extension in the high jumper implies better use of the catapult mechanism. The findings of this study showed that the muscle-tendon interaction differs depending on the jump skill level, suggesting a more efficient neuromuscular control in skilled jumpers.

**Key words:** Ankle plantar flexor, dynamic catch mechanism, force-velocity relationship, force-power relationship, series elastic elements.

## Introduction

Countermovement jump (CMJ) is a fundamental task to assess and monitor neuromuscular function in growth and development, physical fitness, and athletic performance (Hoffman et al., 2005; Isaacs, 1998; Markovic et al., 2004). During a CMJ, a powerful and well-coordinated concentric contraction (propulsion phase) following an eccentric (countermovement phase) contraction occurs (Fukashiro and Komi, 1987). This sequential muscle behavior is referred to as the stretch-shortening cycle (SSC), which is known to enhance muscle force/work during the propulsive phase (Bobbert and Casius, 2005). This enhancement is called the 'SSC effect' (Cavagna et al., 1968).

Previous research has explained how to maximize the SSC effect by comparing the intensity of the tasks (Cormie et al., 2009; McBride, 2021; Salles et al., 2011). They demonstrated that by increasing the use of the joints in the lower extremities, the muscle-tendon unit (MTU) was lengthened, which induced muscle activation and increased tendon work. However, effective performance was achieved in a low-effort task without this MTU interaction (Vanrenterghem et al., 2004). Furthermore, joint kinematics do not fully account for the MTU interaction because asynchronous behavior is observed (Farris et al., 2016; Griffiths, 1991; Kawakami et al., 2002). Therefore, it remains unclear how good and poor jumpers differ in utilizing or optimizing the SSC effect to achieve different levels of performance in human jumps.

The remarkable jumping ability, also known as the catch mechanism, was mostly displayed by invertebrate animals. Gronenberg (1996) showed that a passive structure that deforms to store elastic energy and rapidly recoils maximizes the force and power generated by the muscle (Bennet-Clark, 1975). Recently, this spring-like mechanism has been adapted to explain *in-vivo* human jumping (Farris et al., 2016; Roberts and Azizi, 2011). In muscle-tendon interactions, the tendon acts as an energy conservator by storing elastic energy and serves as a power amplifier by reutilizing the stored elastic energy (Farris et al., 2016; Kawakami et al., 2002; Roberts and Azizi, 2011). Additionally, delayed ankle extension by the proximal joints helps to lengthen the distal tendon and activate it further to store elastic energy (Astley and Roberts, 2014). After training, the altered joint coordination and increased tendon velocity caused an improved SSC effect, resulting in an increased jump height due to greater storage of elastic energy (Cormie et al., 2009; B. W. Hoffman et al., 2022). Therefore, cooperation between joint kinematics and MTU interaction is the key to a dynamic catch mechanism (Robertson et al., 2018). Thus, this investigation aimed to determine whether the joint coordination and MTU interaction differ based on the level of jump skill and jump height during a CMJ.

## Methods

### Participants

Sixteen healthy male subjects who did not have neuromuscular disorders or injuries were recruited. The subjects were divided into two groups based on their maximal jump height: the trained group (TG; n = 8, age: 25.1 ± 1.9 years, height: 178.6 ± 3.5 cm, weight: 78.1 ± 6.1 kg) and the untrained group (UG; n = 8, age: 25.1 ± 1.5 years, height:

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174.4 ± 5.9 cm, weight: 75.8 ± 10.2 kg). Previous studies have reported that healthy male individuals can jump less than 50 cm (B. W. Hoffman et al., 2022) and elite athletes can jump around 50 cm (Tauchi et al., 2008). Therefore, we grouped the subjects based on whether they could jump over 50 cm or not. The untrained group consisted of individuals who did not exercise regularly and could not jump over 50 cm. All participants provided informed consent and participated in the experiments approved by the institutional review board (7001988-202204-HR-1139-03).

### Experimental procedure

All the CMJs were performed with the participants' hands on their hips. Two different types of CMJ jumps were performed: a jump to 20% of their height (CMJ$_{20}$) and the maximum effort jump (CMJ$_{Max}$) (Kim et al., 2014). Before data collection, participants performed a warm-up jump to 10% of their height and received jump height feedback using a laser marker for CMJ$_{20}$. Each task was performed twice, with at least a 1-minute rest period provided between trials. Jump height was measured using the position of the C7 marker.

### Joint kinematics and kinetics

The CMJs were captured using eight 3D motion capture cameras (VICON MX-F20, Oxford Metric Ltd., Oxford, UK) with a sampling rate of 200 Hz and two force plates (AMTI, OR6-7, Watertown, MA) with a sampling rate of 1000 Hz. A modified Helen Hayes marker set (Kadaba et al., 1990) with 30 reflective markers and two cluster markers were used (Farris et al., 2016). Lower extremity joint kinematics and kinetics were calculated using an open-source program (OpenSim 4.1) (Delp et al., 2007). Joint power and force were normalized by each participant's weight. To accommodate the fast jumping movement used in this study. We modified the Lai Arnold 2017 model's ankle dorsal range and contraction velocity to 30 degrees and 15 m/s, respectively, based on a previous running study (Arnold et al., 2013; Thelen et al., 2005). The model was scaled using each participant's anthropometric information.

Ground reaction force (GRF) data and marker data were filtered using a fourth-order low-pass filter with a cut-off frequency of 15 Hz and 30 Hz, respectively. The initiation of the jump was defined as the point when the velocity of the C7 marker exceeded 0.05 m/s, and the propulsion phase was defined as the time when the upward velocity of the center of mass (CoM) exceeded 0.05 m/s. The takeoff phase was set when the GRF was <10 N during a CMJ (Farris et al., 2016). Time was normalized with 101 from the initial phase to takeoff and was represented as a percentage. Relative time of propulsion, peak joint angle, moment and power was calculated.

### Muscle architecture

A portable real-time ultrasound imaging system (LogicScan 128 EXT-12 kit, TELEMED UAD, Vilnius, Lithuania) was used to measure the medial gastrocnemius (MG). A linear probe (LV7.5/60/96Z, Samsung Medison, Seoul, Korea) was placed on the muscular belly, where the superficial and deep aponeurosis were parallel. The architecture was captured during CMJs and collected at a sampling rate of 80 Hz.

The fascicle length (FL) which is the distance between superficial and deep aponeurosis, and the fascicle pennation angle, which is the angle between the FL and deep aponeurosis, were measured using Image-J software (National Institute of Health, MD, USA). To establish the reliability, four participants from each group were randomly analyzed (FL during CMJ; intraclass correlation coefficients between days [ICC] = 0.835-0.997 for CMJ$_{20}$, 0.945 - 0.998 for CMJ$_{Max}$). MTU length was used from the OpenSim program and the tendon length was calculated using the fascicle length and the MTU length (Bobbert et al., 1986a). Fascicle and tendon force were also calculated from the previous equation (Kubo et al., 2000). The physiological cross-sectional area was set at 15.4% (Fukunaga et al., 1996), and the moment arm length was adopted from OpenSim program. The lower limb length, which is the distance between the lateral malleolus and the lateral epicondyle, was measured to normalize the length of the MTU, fascicle, and tendon.

Fascicle shortening velocity was calculated directly using the fascicle length, and was measured as the rate of change in fascicle length. The rate of change in tendon length was measured from the onset of propulsion to just before the peak MG tendon length, and from after the peak MG tendon length to take-off.

### Statistical analysis

Repeated measures ANOVA with Bonferroni post-hoc was conducted using IBM SPSS Statistics 25.0 (Chicago, IL, USA) to examine the interaction effect between the group (TG and UG) and the task (CMJ$_{20}$ and CMJ$_{Max}$). All data were presented as the mean ± s.d. to identify the difference based on tasks and groups and significance was set at $p < 0.05$.

## Results

### Jump height

For CMJ$_{Max}$, the TG jumped higher than the UG ($p < 0.05$) (Table 1). The CMJ$_{20}$ jump height between the groups was not different (Table 1).

**Table 1.** **CoM mechanics during a CMJ.**

| Variables | CMJ$_{20}$ | | CMJ$_{Max}$ | |
|---|---|---|---|---|
| | UG | TG | UG | TG |
| **Jump height (cm)*,**,†, ††** | 36.1 ± 2.7†† | 39.5 ± 5.6†† | 45.2 ± 4.1** | 53.3 ± 3.1 |
| **Peak GRF (N/kg)** | 2.4 ± 0.5 | 2.5 ± 0.2 | 2.3 ± 0.6 | 2.4 ± 0.2 |
| **Peak mechanical power (Watt/kg)†** | 41.2 ± 8.5 | 43.3 ± 5.0 | 45.2 ± 7.7 | 50.6 ± 4.5 |
| **Negative work (J/kg)†** | -3.0 ± 0.3†† | -2.7 ± 0.6†† | -3.6 ± 0.9 | -4.2 ± 0.86 |
| **Positive work (J/kg)†** | 6.6 ± 1.5 | 5.4 ± 1.1 | 7.8 ± 2.2 | 8.2 ± 1.7 |

Significantly different at $p < 0.05$. *TG vs UG regardless of tasks. †CMJ$_{20}$ vs CMJ$_{Max}$ regardless of groups. **TG vs UG in CMJ$_{20}$ or CMJ$_{Max}$. ††TG or UG in CMJ$_{20}$ vs CMJ$_{Max}$.

## Joint kinematics and kinetics

Regardless of groups, the peak mechanical power and positive and negative work increased significantly in CMJ$_{Max}$ ($p < 0.05$) (Table 1). In both groups, the peak ankle joint angle did not change during the task, the peak hip and knee joint angles were increased in CMJ$_{Max}$ compared to in CMJ$_{20}$ ($p < 0.05$) (Figure 1A). When compared to CMJ$_{20}$, CMJ$_{Max}$ had faster hip, knee, and ankle joint velocities in both groups ($p < .05$) (Figure 1B). A greater hip joint moment was observed in CMJ$_{Max}$ (UG; 1.8 ± 0.5 Nm/kg, TG; 2.1 ± 0.5 Nm/kg) compared with CMJ$_{20}$ (UG; 1.3 ± 0.4 Nm/kg, TG; 1.6 ± 0.4 Nm/kg), but the peak moment of other joints was not different between tasks. However, the power of all joints was significantly increased at all joints during the CMJ$_{Max}$ compared to CMJ$_{20}$ ($p < 0.05$) (Figure 1C).

Regardless of grouping, the onset of the propulsion phase started relatively earlier in CMJ$_{Max}$ compared to CMJ$_{20}$ (Table 2). During a CMJ$_{Max}$, the initiation of the hip and knee joint extension appeared earlier than CMJ$_{20}$ (Table 2). However, the peak power at the knee joint occurred relatively later in CMJ$_{Max}$.

Both groups showed greater negative work during CMJ$_{Max}$ (UG: -3.6 ± 0.9 J/kg, TG: -4.2 ± 0.9 J/kg) compared to CMJ$_{20}$ (UG: -3.0 ± 0.3 J/kg, TG: -2.7 ± 0.6 J/kg). However, there were no differences between groups in joint kinematics and kinetics (Figure 2). The TG group showed relatively delayed extension of the ankle joint and the peak hip joint moment and power compared to the UG group (Table 2). However, the change in the length of the MTU and tendon did not differ between groups.

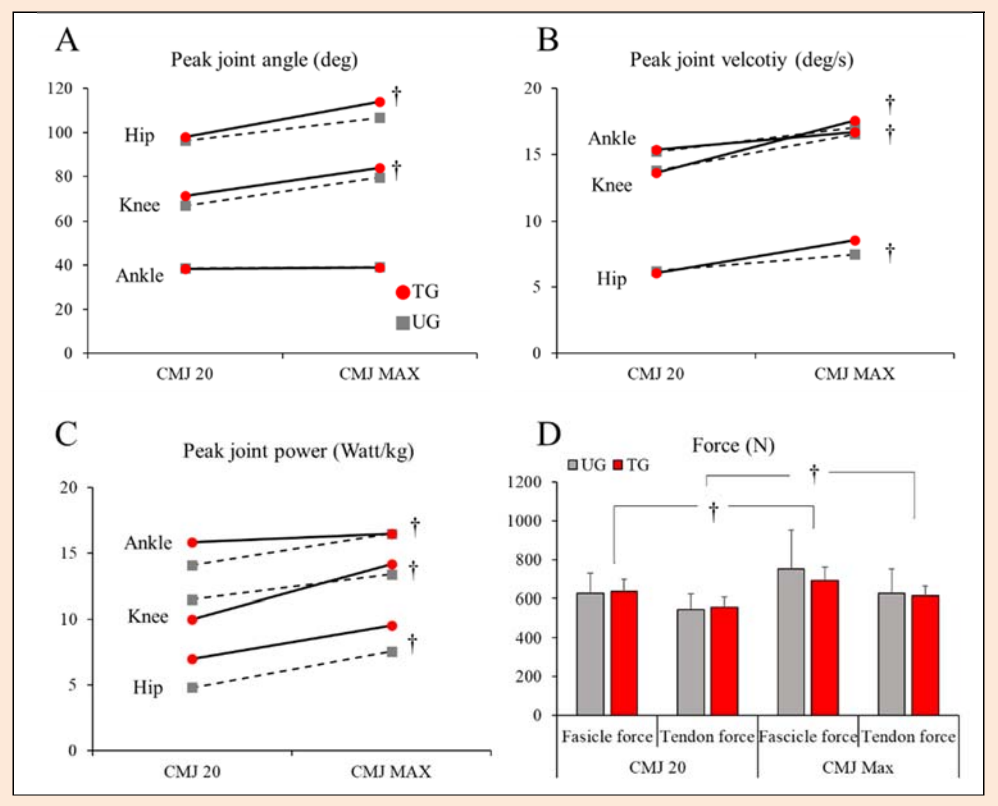

**Figure 1.** **Joint kinematics and kinetics and MTU behavior at CMJ$_{20}$ and CMJ$_{Max}$. Significantly different at $p < .05$ with tasks regardless of groups (†).**

**Table 2.** **Relative time of propulsion, joint kinematics and kinetics, and MTU behavior during a CMJ.**

| Time (%) | CMJ$_{20}$ | | CMJ$_{Max}$ | |
|---|---|---|---|---|
| | UG | TG | UG | TG |
| **Propulsion phase**$^{\dagger}$ | 71.9 ± 3.4 | 75.4 ± 3.9 | 70.0 ± 6.2 | 70.6 ± 4.9 |
| **Onset of hip extension**$^{\dagger}$ | 68.9 ± 3.0 | 72.1 ± 4.2 | 67.0 ± 7.0 | 65.9 ± 9.0 |
| **Onset of knee extension**$^{\dagger}$ | 71.9 ± 4.3 | 75.8 ± 3.3 | 70.9 ± 5.2 | 71.1 ± 5.3 |
| **Onset of ankle extension**$^{*}$ | 71.4 ± 8.8 | 80.9 ± 2.3 | 72.0 ± 8.2 | 77.6 ± 6.1 |
| **Peak hip joint moment**$^{*,\dagger}$ | 74.8 ± 5.4 | 85.9 ± 5.1 | 72.6 ± 6.8 | 78.1 ± 9.6 |
| **Peak knee joint moment**$^{\dagger,\dagger\dagger}$ | 79.1 ± 6.8 | 85.0 ± 5.4$^{\dagger\dagger}$ | 75.9 ± 7.5 | 75.9 ± 10.1 |
| **Peak ankle joint moment**$^{\dagger}$ | 87.1 ± 4.2 | 91.3 ± 3.3 | 85.0 ± 6.9 | 85.9 ± 9.4 |
| **Peak hip joint power**$^{*}$ | 85.6 ± 3.3 | 90.1 ± 1.6 | 85.5 ± 7.5 | 90.4 ± 5.7 |
| **Peak knee joint power**$^{\dagger}$ | 92.8 ± 3.9 | 92.9 ± 2.4 | 95.3 ± 2.5 | 96.1 ± 1.6 |
| **Peak ankle joint power** | 96.4 ± 1.3 | 97.1 ± 1.4 | 96.9 ± 1.6 | 97.4 ± 1.6 |
| **Onset of MG MTU shortening** | 87.5 ± 4.6 | 90.0 ± 1.8 | 90.9 ± 5.1 | 91.4 ± 4.4 |
| **Max MG tendon length**$^{*}$ | 90.0 ± 4.1 | 92.1 ± 1.5 | 91.6 ± 5.7 | 95.3 ± 1.3 |

Significantly different at $p < .05$. *TG vs UG regardless of tasks. †CMJ$_{20}$ vs CMJ$_{Max}$ regardless of groups. ††TG or UG in CMJ$_{20}$ vs CMJ$_{Max}$.

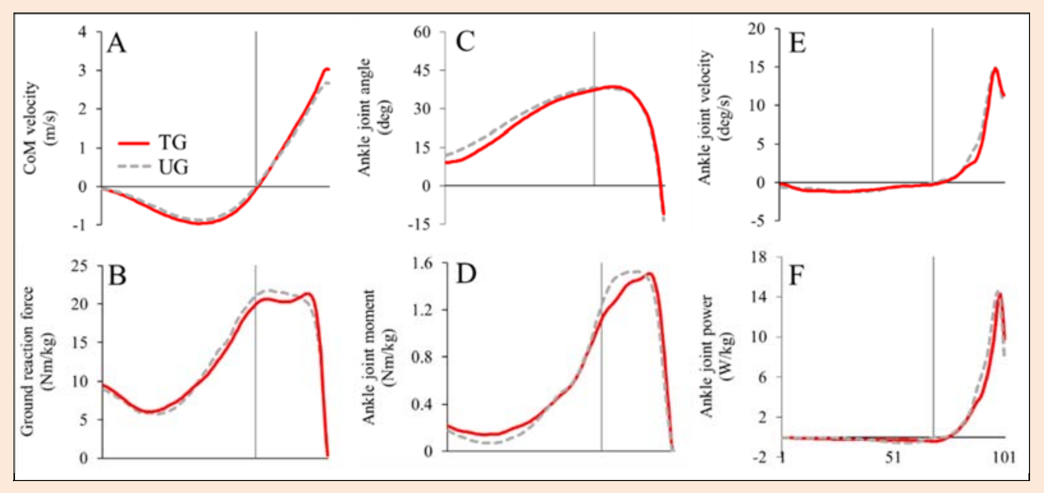

**Figure 2. Ankle joint kinematics and kinetics at CMJ$_{Max}$.** Jumping data in UG and TG during CMJ$_{Max}$ was normalized with 101 from the initial phase to takeoff. A vertical black line represents the propulsion time for each group at CMJ$_{Max}$.

## MTU behavior

The magnitude of the MTU shortening of the MG did not differ between the tasks, but, the MTU lengthening of the MG was increased during CMJ$_{Max}$ (16.9 ± 4.9 mm) compared to CMJ$_{20}$ (10.9 ± 5.2 mm). Although the MTU length was changed, the changes in the length of the fascicle and tendon were not observed.

Regardless of the groups, fascicle force (CMJ$_{20}$: 631.92 ± 82.30 N, CMJ$_{Max}$: 721.3 ± 147.3 N) and tendon force (CMJ$_{20}$: 552.5 ± 62.9 N, CMJ$_{Max}$: 620.09 ± 92.02 N) increased as task intensity increased ($p < 0.05$). The rate of change in tendon length after the maximum tendon length was greater during CMJ$_{Max}$ compared to CMJ$_{20}$ (Figure 3F) ($p < 0.05$).

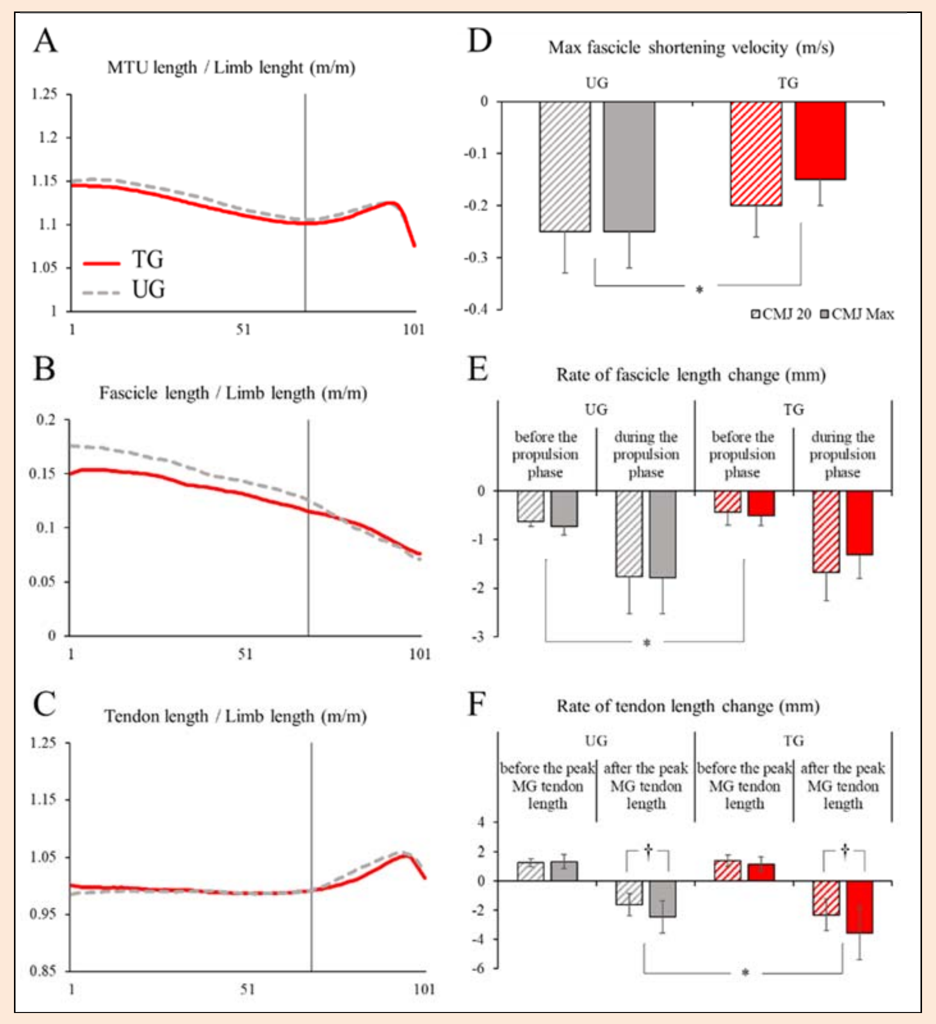

**Figure 3. MTU behavior during CMJ$_{MAX}$ (A-C) and muscle mechanics during CMJ (D-F).** Significantly different at $p < 0.05$ with groups regardless of trials (*) and tasks regardless of groups (†).

Before the propulsive phase, the rate of change in fascicle length was smaller in the TG group than in the UG group (Figure 3B) ($p < 0.05$). Similarly, the fascicle shortening velocity did differ between groups (UG: -0.3 ± 0.1 m/s, TG: -0.2 ± 0.1 m/s, average values for a CMJ) ($p < 0.05$). However, the rate of change in tendon length did not differ between the groups.

## Discussion

The purpose of this study was to determine whether (1) the interaction between joints and MTU and (2) the utilization of the dynamic catch mechanism differ depending on the level of jump skill. Our results showed that both TG and UG use the generally accepted mechanism (Bobbert et al., 1986b), which utilizes the elastic energy stored in the MTU. However, individuals who showed higher jump height appeared to be better able to maximize the SSC effect by utilizing a more efficient dynamic catch-like mechanism.

### Jump strategy to enhance jump height regardless of groups

The total work critical to achieving jump height was determined by the power generated at each joint during the propulsion phase (Vanezis and Lees, 2005; Vanrenterghem et al., 2004). Similar to previous studies that emphasized the use of proximal joints (Bobbert et al., 1996; Fukashiro and Komi, 1987; Nikolaidou et al., 2017), TG and UG accentuated the negative work, which was enhanced by about 38% during $CMJ_{Max}$ compared to $CMJ_{20}$. Both groups were also propelled with fast joint velocity, indicating that they employed a joint strategy aimed at increasing the power by maximizing the magnitude and the velocity of force production.

When performing a low-effort task without MTU interaction, the performance is achieved effectively. However, as the task intensity increases, the behavior becomes more crucial for enhancing the SSC effect as previous studies have shown (Vanrenterghem et al., 2004). In terms of joints strategy, greater countermoves and fast-extending proximal joints were favorable to generating greater force by activating muscles and storing elastic energy (Astley and Roberts, 2014; Salles et al., 2011). Performance at the optimum length or velocity, which increases the potential for force and power production according to the force-length or velocity relationship, is enhanced by MTU interaction (Kawakami et al., 2002). However, our study found that the velocity is more dedicated to using elastic energy rather than changing the length. The faster recoil velocity at $CMJ_{Max}$ could maximize the ankle joint power at $CMJ_{Max}$, which increased by about 9.9% compared to $CMJ_{20}$. Therefore, TG and UG jumped with coordinated use of joints and MTU to increase the usage of elastic energy.

### The catapult-like jumping mechanism in TG

Both TG and UG groups used joints and elastic energy to attempt to jump higher, in line with previous research (McErlain-Naylor et al., 2014). However, the difference in jump height between the group could not be fully explained by the magnitude of these factors alone. According to Cormie et al. (2009), not only the peak value of variables but also its timing was important for achieving height. Our results suggest that the jumping strategy in TG was similar to the efficient dynamic catapult mechanism.

To further lengthen the tendon length and optimize force production, TG utilized a strategy of extending the ankle joint as late as possible and early extension of proximal joints. This resulted in the tendon being stretched further, allowing the fascicle to produce force around the optimal length with low velocity (Kawakami et al., 2002). The almost isometrical shortening during the force generation phase in TG suggested that they had a neuro-mechanical advantage in generating higher force than UG for a given level of muscle activation. However, when the muscle shortening velocity was low, the power potential was diminished by the power-velocity relationship. Nevertheless, the tendon still enabled the muscle to generate greater force at the optimal fascicle length states and amplified the power (Farris et al., 2016; Kawakami et al., 2002; Roberts and Azizi, 2011).

In addition, it is important to note that producing greater force in the concentric phase is highly dependent on the rapid force development at the eccentric phase in the early propulsion phase (Krzyszkowski et al., 2022; Sole et al., 2018). Our study showed that the GRF in TG was higher at the end of propulsion compared to the beginning, whereas in UG, the concentric force appeared to slightly decrease despite high GRF at the early propulsion. This suggests that even with consecutively transferred power, the power generated in the hip joint may not fully transmit to the ankle joint in UG (Prilutsky and Zatsiorsky, 1994). Consequently, additional muscle work might be required in UG to generate large joint force and power. Additionally, the delayed ankle joint extension and instantaneous recoiled elastic energy in TG might have contributed to slightly increased concentric force, but, further researches is needed to investigate this.

## Conclusion

The aim of our study was to examine the disparities in the joint movement and muscle-tendon interaction in the lower extremity between trained and untrained individuals during a countermovement jump. As the intensity of the jump increased, both groups displayed improved joint kinematics and kinetics; however, these changes alone were not sufficient to account for the difference in jump height between the two groups in $CMJ_{Max}$. It appears that the difference in muscle-tendon interaction, also referred to the dynamic catapult-like mechanism, is crucial factor that explain the variation in jump height between TG and UG in $CMJ_{Max}$.

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## References

Alexander, R. M. and Bennet-Clark, H. C. (1977) Storage of elastic strain energy in muscle and other tissues. *Nature* **265(5590)**, 114-117. https://doi.org/10.1038/265114a0

Anderson, F. C. and Pandy, M. G. (1993) Storage and utilization of elastic strain energy during jumping. *Journal of biomechanics* **26(12)**, 1413-1427. https://doi.org/10.1016/0021-9290(93)90092-s

Arnold, E. M., Hamner, S. R., Seth, A., Millard, M. and Delp, S. L. (2013) How muscle fiber lengths and velocities affect muscle force generation as humans walk and run at different speeds. *Journal of Experimental Biology* **216(11)**, 2150-2160. https://doi.org/10.1242/jeb.075697

Astley, H. C. and Roberts, T. J. (2014) The mechanics of elastic loading and recoil in anuran jumping. *Journal of Experimental Biology* **217(24)**, 4372-4378. https://doi.org/10.1242/jeb.110296

Bennet-Clark, H. (1975) The energetics of the jump of the locust Schistocerca gregaria. *Journal of Experimental Biology* **63(1)**, 53-83. https://doi.org/10.1242/jeb.63.1.53

Bobbert, M. F. and Casius, L. J. (2005) Is the effect of a countermovement on jump height due to active state development? *Medicine and science in sports and exercise* **37(3)**, 440-446. https://doi.org/10.1249/01.mss.0000155389.34538.97

Bobbert, M.F., Huijing P.A. and van Ingen Schenau, G. J. (1986a) A model of the human triceps surae muscle-tendon complex applied to jumping. *Journal of biomechanics* **19(11)**, 887-898. https://doi.org/10.1016/0021-9290(86)90184-3

Bobbert, M. F., Huijing, P. A. and van Ingen Schenau, G. J. (1986b) An estimation of power output and work done by the human triceps surae musle-tendon complex in jumping. *Journal of Biomechanics* **19(11)**, 899-906. https://doi.org/10.1016/0021-9290(86)90185-5

Bobbert, M. F., Gerritsen, K. G., Litjens, M. C. and Van Soest, A. J. (1996) Why is countermovement jump height greater than squat jump height? *Medicine and science in sports and exercise* **28(11)**, 1402-1412. https://doi.org/10.1097/00005768-199611000-00009

Bosco, C., Viitasalo, J. T., Komi, P. V. and Luhtanen, P. (1982) Combined effect of elastic energy and myoelectrical potentiation during stretch-shortening cycle exercise. *Acta Physiologica Scandinavica* **114(4)**, 557-565. https://doi.org/10.1111/j.1748-1716.1982.tb07024.x

Cavagna, G. A., Dusman, B. and Margaria, R. (1968) Positive work done by a previously stretched muscle. *Journal of Applied Physiology* **24(1)**, 21-32. https://doi.org/10.1152/jappl.1968.24.1.21

Cormie, P., McBride, J. M. and McCaulley, G. O. (2009) Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *The Journal of Strength & Conditioning Research* **23(1)**, 177-186. https://doi.org/10.1519/JSC.0b013e3181889324

Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., . . . Thelen, D. G. (2007) OpenSim: open-source software to create and analyze dynamic simulations of movement. IEEE *Transactions on Biomedical Engineering* **54(11),** 1940-1950. https://doi.org/10.1109/TBME.2007.901024

Farris, D. J., Lichtwark, G. A., Brown, N. A. and Cresswell, A. G. (2016) The role of human ankle plantar flexor muscle-tendon interaction and architecture in maximal vertical jumping examined in vivo. *Journal of Experimental Biology* **219(4)**, 528-534. https://doi.org/10.1242/jeb.126854

Fukashiro, S. and Komi, P. (1987) Joint moment and mechanical power flow of the lower limb during vertical jump. *International Journal of Sports Medicine* **8 Suppl 1**, 15-21. https://doi.org/10.1055/s-2008-1025699

Fukunaga, T., Roy, R. R., Shellock, F. G., Hodgson, J. A. and Edgerton, V. R. (1996) Specific tension of human plantar flexors and dorsiflexors. *Journal of Applied Physiology* **80(1)**, 158-165. https://doi.org/10.1152/jappl.1996.80.1.158

Griffiths, R. I. (1991) Shortening of muscle fibres during stretch of the active cat medial gastrocnemius muscle: the role of tendon compliance. *The Journal of physiology* **436**, 219-236. https://doi.org/10.1113/jphysiol.1991.sp018547

Gronenberg, W. (1996) Fast actions in small animals: springs and click mechanisms. *Journal of Comparative Physiology A* **178(6)**, 727-734. https://doi.org/10.1007/BF00225821

Hoffman, B. W., Raiteri, B. J., Connick, M. J., Beckman, E. M., Macaro, A., Kelly, V. G. and James, L. P. (2022) Altered countermovement jump force profile and muscle-tendon unit kinematics following combined ballistic training. *Scandinavian Journal of Medicine & Science in Sports*. https://doi.org/10.1111/sms.14211

Hoffman, J. R., Ratamess, N. A., Cooper, J. J. and Kang, J. (2005) Comparison of loaded and unloaded jump squat training on strength/power performance in college football players. *Journal of Strength and Conditioning Research* **19(4)**, 810. https://doi.org/10.1519/R-16774.1

Isaacs, L. D. (1998) Comparison of the vertec and just jump systems for measuring height of vertical jump by young children. *Perceptual and motor skills* **86(2)**, 659-663. https://doi.org/10.2466/pms.1998.86.2.659

Kadaba, M. P., Ramakrishnan, H. K. and Wootten, M. E. (1990) Measurement of lower extremity kinematics during level walking. *Journal of orthopaedic research* **8(3)**, 383-392. https://doi.org/10.1002/jor.1100080310

Kawakami, Y., Muraoka, T., Ito, S., Kanehisa, H. and Fukunaga, T. (2002) In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity. *The Journal of physiology* **540(2)**, 635-646. https://doi.org/10.1113/jphysiol.2001.013459

Kim, S., Park, S. and Choi, S. (2014) Countermovement strategy changes with vertical jump height to accommodate feasible force constraints. *Journal of biomechanics* **47(12)**, 3162-3168. https://doi.org/10.1016/j.jbiomech.2014.06.013

Krzyszkowski, J., Chowning, L. D. and Harry, J. R. (2022) Phase-specific predictors of countermovement jump performance that distinguish good from poor jumpers. *Journal of Strength and Conditioning Research* **36(5)**, 1257-1263. https://doi.org/10.1519/JSC.0000000000003645

Kubo, K., Kanehisa, H., Takeshita, D., Kawakami, Y., Fukashiro, S. and Fukunaga, T. (2000) In vivo dynamics of human medial gastrocnemius muscle-tendon complex during stretch-shortening cycle exercise. *Acta Physiologica Scandinavica* **170(2)**, 127-135. https://doi.org/10.1046/j.1365-201x.2000.00768.x

Kurokawa, S., Fukunaga, T. and Fukashiro, S. (2001) Behavior of fascicles and tendinous structures of human gastrocnemius during vertical jumping. *Journal of Applied Physiology* **90(4)**, 1349-1358. https://doi.org/10.1152/jappl.2001.90.4.1349

Kurokawa, S., Fukunaga, T., Nagano, A. and Fukashiro, S. (2003) Interaction between fascicles and tendinous structures during counter movement jumping investigated in vivo. *Journal of Applied Physiology* **95(6)**, 2306-2314. https://doi.org/10.1152/japplphysiol.00219.2003

Markovic, G., Dizdar, D., Jukic, I. and Cardinale, M. (2004) Reliability and factorial validity of squat and countermovement jump tests. *The Journal of Strength & Conditioning Research* **18(3)**, 551-555.

McBride, J. M. (2021) Muscle Actuators, Not Springs, Drive Maximal Effort Human Locomotor Performance. *Journal of Sports Science & Medicine* **20(4)**, 766. https://doi.org/10.52082/jssm.2021.766

McErlain-Naylor, S., King, M. and Pain, M. T. G. (2014) Determinants of countermovement jump performance: a kinetic and kinematic analysis. *Journal of Sports Sciences* **32(19)**, 1805-1812. https://doi.org/10.1080/02640414.2014.924055

Nikolaidou, M. E., Marzilger, R., Bohm, S., Mersmann, F. and Arampatzis, A. (2017) Operating length and velocity of human M. vastus lateralis fascicles during vertical jumping. *Royal Society Open Science* **4(5)**, 170185. https://doi.org/10.1098/rsos.170185

Oh, J. and Lee, H.-D. (2022) Influence of eccentric strength of knee extensor muscles on biomechanical factors of a vertical drop jump. *Journal of Electromyography and Kinesiology* 102648. https://doi.org/10.1016/j.jelekin.2022.102648

Prilutsky, B. I. and Zatsiorsky, V. M. (1994) Tendon action of two-joint muscles: transfer of mechanical energy between joints during jumping, landing, and running. *Journal of biomechanics* **27(1)**, 25-34. https://doi.org/10.1016/0021-9290(94)90029-9

Roberts, T. J. and Azizi, E. (2011) Flexible mechanisms: the diverse roles of biological springs in vertebrate movement. *Journal of experimental biology* **214(3)**, 353-361. https://doi.org/10.1242/jeb.038588

Robertson, J. W., Struthers, C. N. and Syme, D. A. (2018) Enhancement of muscle and locomotor performance by a series compliance: a mechanistic simulation study. *Plos One* **13(1)**, e0191828. https://doi.org/10.1371/journal.pone.0191828

Salles, A. S., Baltzopoulos, V. and Rittweger, J. (2011) Differential effects of countermovement magnitude and volitional effort on vertical jumping. *European Journal of Applied Physiology* **111(3)**, 441-448. https://doi.org/10.1007/s00421-010-1665-6

Seiberl, W., Power, G. A., Herzog, W. and Hahn, D. (2015) The stretch-shortening cycle (SSC) revisited: residual force enhancement contributes to increased performance during fast SSCs of human m. adductor pollicis. *Physiological reports* **3(5)**. https://doi.org/10.14814/phy2.12401

Sole, C. J., Mizuguchi, S., Sato, K., Moir, G. L. and Stone, M. H. (2018) Phase characteristics of the countermovement jump force-time curve: A comparison of athletes by jumping ability. *The Journal of Strength & Conditioning Research* **32(4)**, 1155-1165. https://doi.org/10.1519/JSC.0000000000001945

Tauchi, K., Endo, T., Ogata, M., Matsuo, A. and Iso, S. (2008) The characteristics of jump ability in elite adolescent athletes and healthy males: the development of countermovement and rebound jump ability. *International Journal of Sport and Health Science* **6**, 78-84. https://doi.org/10.5432/ijshs.6.78

Thelen, D. G., Chumanov, E. S., Best, T. M., Swanson, S. C. and Heiderscheit, B. C. (2005) Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. *Medicine & Science in Sports & Exercise* **37(11)**, 1931-1938. https://doi.org/10.1249/01.mss.0000176674.42929.de

Tomalka, A., Weidner, S., Hahn, D., Seiberl, W. and Siebert, T. (2020) Cross-Bridges and Sarcomeric Non-cross-bridge Structures Contribute to Increased Work in Stretch-Shortening Cycles. *Frontiers in physiology* **11**, 921. https://doi.org/10.3389/fphys.2020.00921

van Ingen Schenau, G. J., Bobbert, M. F. and de Haan, A. (1997a) Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics* **13(4)**, 389-415. https://doi.org/10.1123/jab.13.4.389

van Ingen Schenau, G. J., Bobbert, M. F. and de Haan, A. (1997b) Mechanics and energetics of the stretch-shortening cycle: a stimulating discussion. *Journal of applied Biomechanics* **13(4)**, 484-496. https://doi.org/10.1123/jab.13.4.484

Vanezis, A. and Lees, A. (2005) A biomechanical analysis of good and poor performers of the vertical jump. *Ergonomics* **48(11)**, 1594-1603. https://doi.org/10.1080/00140130500101262

Vanrenterghem, J., Lees, A., Lenoir, M., Aerts, P. and De Clercq, D. (2004) Performing the vertical jump: movement adaptations for submaximal jumping. *Human movement science* **22(6)**, 713-727. https://doi.org/10.1016/j.humov.2003.11.001

## Key points

- As jump intensity increases, the kinematics and kinetics of the lower extremity enhance as expected, regardless of jumping skill level.
- But, the higher jumping group seems to utilize the dynamic catapult-like mechanism better.
- When analyzing jump performance, muscle-tendon interaction, in addition to joint coordination, should be considered an essential factor.

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