INTER-JOINT DIFFERENCES EXIST IN KINETIC DEMAND FOR PERFORMANCE IN HIGH JUMP

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We aimed to clarify the lower-limb kinetic determinants of inter-individual variability in flight height in the high jump. We hypothesised that although the take-off of the high jump requires great external power, the proximal (hip) joint is required to function as a stabiliser rather than as a power generator for higher performance. We analysed high jump motions by 16 male high jumpers. For the hip joint, only maximum torque significantly correlated with the flight height. Meanwhile, for the knee joint, both peak positive power and peak torque were correlated with the flight height, with a stronger correlation for power than for torque. We found that the kinetic requirement for performance differs between joints, which provides the practical implication that the musculoskeletal functions to be trained differ between joints, such as torque exertion for the hip and power exertion for the knee.

KEYWORDS: torque, power, work, Fosbury flop, three-dimension.

INTRODUCTION: High jump is the most height-specific jumping mode in humans. Jumping higher can be described as acquiring the mechanical energy directly contributing the centre of mass (COM) height (E_{vert}; sum of vertical-kinetic and gravitational-potential energies). In high jump take-off, athletes must generate larger E_{vert} during a limited duration take-off (<0.2 s). Therefore, improving the power exertion (i.e., the rate of energy generation) ability has been assumed to be important for higher jumping (Suchomel et al., 2016).

Several studies on a running jump (Stefanyshyn and Nigg, 1998; Sado et al., 2018) have examined joint power exertion and have shown the main power generators are the hip abductors, knee extensors and ankle plantar flexors. These main generators exhibit a power pattern of absorption followed by generation. Meanwhile, the hip extensors exerted positive power during the early take-off phase, but their power is relatively small compared to the main generators (Sado et al., 2018). These studies have clarified how power generation in the running jump is executed; however, it is unclear which power generator is related to the inter-individual variability of performance (i.e., COM height).

In the high jump, E_{vert} is acquired not only via joint power/work exertion during the take-off, but also via the conversion from horizontal kinetic energy acquired via approach to E_{vert} (Sado et al., 2020a). Because of this energy conversion, E_{vert} increases from the early (10%~) take-off phase (Sado et al., 2020a) even when the joint powers of main generators are negative (Sado et al., 2018). An enhancement in this energy conversion can also improve performance. Meanwhile, the approach velocity (and thus, horizontal kinetic energy) in the high jump is sub-maximal even in world-elite athletes (Isolehto et al., 2007), as excessively fast approaches can cause the excessive take-off leg flexion and failure to execute the take-off in the early take-off phase (Dapena et al., 1990). Thus, the take-off leg needs to withstand a large ground reaction force (GRF), which peaks at the very early take-off phase (Sado et al., 2020a), to maintain posture. This ability might become one of the determinants of performance. The lower-limb joint torques peak in a proximal-to-distal sequence, with hip torque peaking at the very early take-off phase (Sado et al., 2018). Thus, the hip joint may be required to act as a “stabiliser” to maintain posture by exerting large joint torque for better performance. Taken together, inter-joint differences in the functional requirement for performance might exist.

We investigated the relationship between joint kinetics and flight height in the high jump with the *a priori* hypotheses that not all joint power and work exertions are related to the flight height and that joint torque at the hip joint is related to the flight height in the high jump.

METHODS: The participants were 16 male high jumpers (mean ± SD of age, 22.6 ± 3.2 years; body height, 1.80 ± 0.06 m; body mass, 68.2 ± 5.8 kg; high jump personal best record (PB), 2.14 ± 0.11 m [range: 1.90–2.35 m]; season best record (SB), 2.11 ± 0.12 m [range: 1.80–2.30 m]. All participants provided written informed consent. They performed high jump trials on the high jump pit in an indoor field with the bar height was set at 90% of SB. The measurement process using cluster and calibration markers was executed similar to Sado et al. (2020b). The participants wore their own high jump shoes with spikes. High jump trials were repeated until either ten trials were performed, or the participant successfully completed three trials in which they took off from the force platform without protruding off the edge and cleared the bar. All participants were instructed to jump as high as possible regardless of the bar height. The three-dimensional coordinates of the reflective markers were recorded by using a 27-camera motion capture system (Vicon motion systems, UK) with a sampling rate of 250 Hz. GRF of the take-off were collected using two force platforms (9287C, Kistler, Switzerland) at a sampling rate of 1000 Hz. Marker data and GRF data were synchronised by the motion capture system.

Position coordinates of reflective markers were smoothed using a Butterworth low-pass digital filter with a cut-off frequency of 14 Hz determined via a residual analysis (Winter, 2009). GRF data were smoothed using the same filter with that of the marker position data (Bisseling and Hof, 2006). COM and the segment inertial parameters were calculated using scaling estimation equations (Dumas et al., 2015). Flight height was defined as the vertical displacement of COM during the flight phase. We analysed the take-off phase from the instant of touch-down to the instant of toe-off. These instants were determined by using the vertical GRF with the threshold of 10 N. The Joint torques at the hip, knee, and ankle of the take-off leg were calculated using the Newton-Euler equation. Anatomical joint torque was calculated by using a joint coordinate system. We used the magnitude (norm of joint torque vector) and anatomical torques for further analysis. Joint torque power was calculated as the dot product of joint angular velocity and torque (Sado et al., 2017). Joint work was calculated by time integrating the joint torque power. We used the mean value of three high jump trials as the representative value for each participant. The normal distribution of each data was assessed with the Kolmogorov-Smirnov test. If the normality was confirmed, Pearson's correlation coefficient (r) was used, else Spearman's rank correlation coefficient (ρ) was used to assess the correlation between flight height and each variable. Statistical significance was set as $p < 0.05$.

RESULTS: GRF peaked at the early take-off phase (24 ± 6%take-off phase) (Figure 1A). External power was negative followed by positive; it peaked at 71 ± 2% take-off phase (Figure 1B). Lower-limb joints exerted extension or abduction torques for most of the take-off phase, with a proximal-to-distal sequence in peak timings (hip: 24 ± 6%, knee: 37 ± 5%, ankle: 55 ± 11%take-off phase) (Figure 2A–C). The hip abduction/adduction, knee extension/flexion and ankle plantar/dorsiflexion power exhibited patterns of negative followed by positive (Figure 2D–F). We observed a proximal-to-distal sequence of peak positive power (hip: 48 ± 3%, knee: 70 ± 3%, ankle: 76 ± 2%take-off phase).

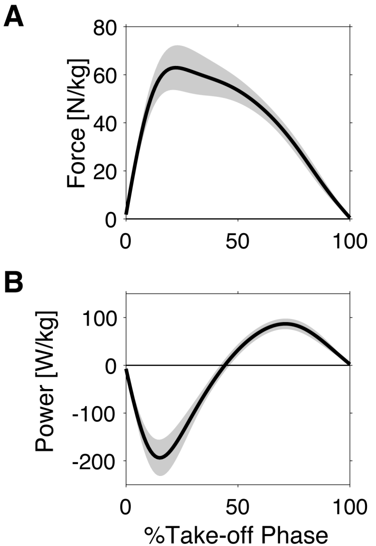

Figure 1: Ensemble averages of norm of ground reaction force (A), and external power (B).

Peak norms of the hip and knee joint torques were significantly correlated with the flight height (Figure 3A–C). Peak positive power was significantly correlated with flight height only for the knee joint (Figure 3E). No significant correlation was found between peak negative joint torque power and flight height in any joints ($|r|$ or $|\rho| < 0.427$, $p > 0.099$).

In most participants (14 of 16), joint work was negative at the hip (-0.79 ± 0.50 J/kg) and knee (-0.76 ± 0.36 J/kg), while it was positive at the ankle (0.29 ± 0.23 J/kg), resulting in the total work of lower-limb joints being negative (-1.26 ± 0.85 J/kg). No significant correlation was found between net joint work and flight height in any joints or in the total of lower-limb joints ($p > 0.149$).

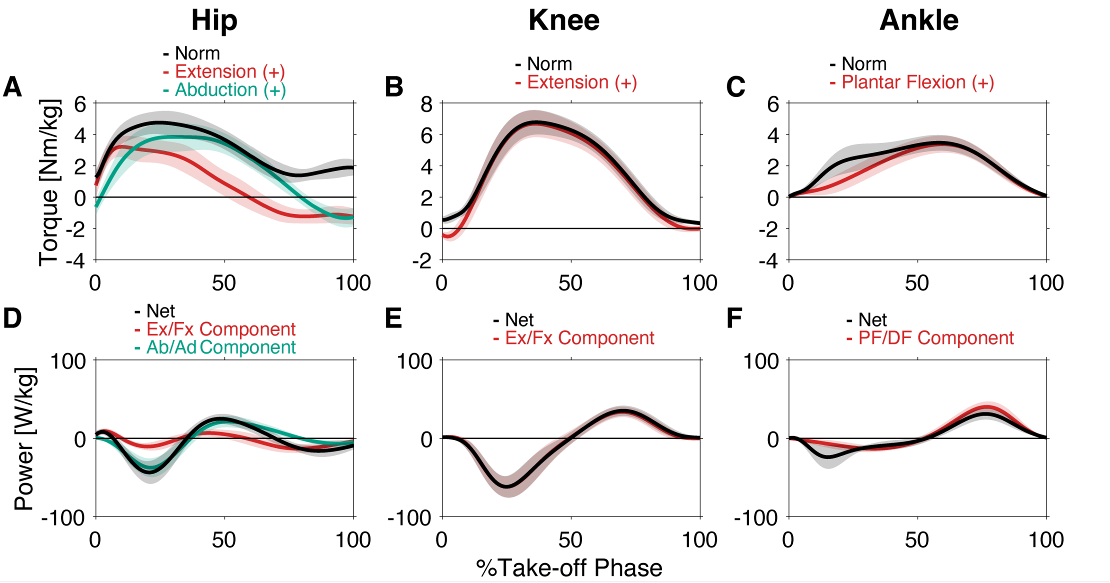

Figure 2: Ensemble averages of time series joint kinetic data.
Joint torque (A–C), and joint torque power (D–F).

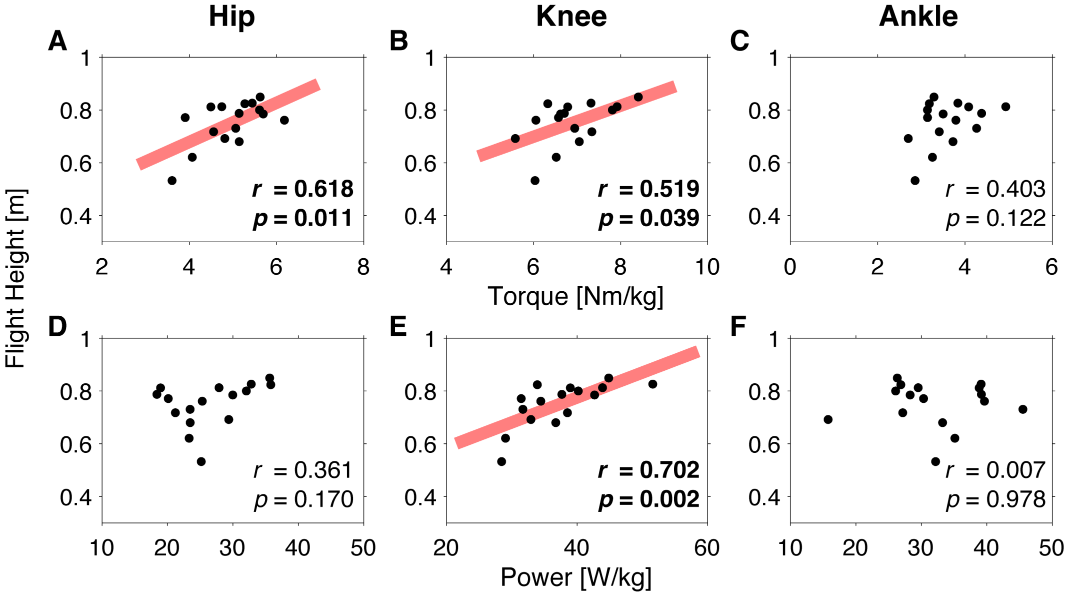

Figure 3: Relationship between flight height and peak joint torque or power.
Correlation between flight height and peak norm of joint torque (A–C), flight height and peak positive joint torque power (D–F). *n* = 16.

DISCUSSION: We found that the hip joint had the strongest correlation to flight height in peak torque among all joints, whereas the knee joint had the strongest correlation in peak positive power among all joints, supporting our hypothesis. The norm of the hip joint torque peaked near the peak of GRF, suggesting that the hip acts as a stabiliser by withstanding large GRF during the early take-off phase. It has been revealed that a faster approach is required for higher jumping (Dapena et al., 1990), which would be accompanied by a larger GRF. Thus, greater hip joint torque is required to stabilise posture against larger GRF. The positive knee power peaked at the late take-off phase. The knee extensors were shown to accelerate the body upwards more during the late take-off phase (Sado et al., 2020a). The present study further suggests that knee extensor power exertion is required for high jump performance.

We found that total of lower-limb net joint works was negative in most participants, and it was not significantly correlated with flight height. This result implies that the energy absorption/generation by lower-limb during the take-off does not necessarily affect the inter-individual variability in high jump performance. In the high jump, COM already has kinetic energy at the beginning of the take-off phase due to the approach, and COM mechanical energy is less at the end than at the beginning. Theoretically, achieved COM height can be increased either by increasing the rate of energy conversion (i.e., reducing negative work) or by increasing the energy at the beginning of the take-off phase (i.e., faster approach). Our result suggests that high jumpers can achieve high performance even if they lose some energy during the take-off.

The practical implication of our findings is that different training strategies (prioritising torque or power) should be applied to each joint to improve high jump performance. Plyometric training is considered to effectively increase power exertion ability, while resistance training improves torque exertion ability (ESS de Villarreal et al., 2010). Currently, the power exertion ability is considered important for jumpers (Suchomel et al., 2016). We further suggest prioritising plyometric training for knee function and resistance training for hip function.

CONCLUSION: We found that the main kinetic determinants of flight height in the lower-limb joints were peak torque in the hip and peak positive power in the knee. We provide an example that even in the most power-demanding task, power is not necessarily the most important at the joint level, and that the functional requirements vary between joints even in the same motor task. Our findings provide insight for athletes on how to optimise training for each joint, specifically whether to focus on power or torque exertion ability.

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ACKNOWLEDGEMENTS: This work was supported by JSPS KAKENHI (21K17592) to N.S.