DISTAL JOINT KINETICS ARE ASSOCIATED WITH SHOT PUT PERFORMANCE

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Shot put motion exhibits upper-limb “push type proximal-to-distal sequence”, which is a common motor task with the lower limb. In the lower limb, proximal muscle function is associated with motor performance. Here we show the strong correlation of the wrist torque and power with the flight distance in the motion of 13 male shot putters. For the shoulder, only the peak torque correlated with the flight distance, whereas for the elbow, flexion torque was exerted, and both torque and power did not correlate with the flight distance. We suggest that it is important for shot putters to strengthen both the torque and power exertion abilities in the wrist and to prioritise the torque exertion ability in the shoulder. We open a novel perspective for training strategies to maximise upper limb motor performance.

KEYWORDS: Wrist joint, Palmar flexion, Torque, Power.

INTRODUCTION: Upper and lower limbs occur "push type proximal to distal sequence” (push type PD sequence) during full strength exercise. It is generally recognised that the proximal musculoskeletal function is important for motor performance (Serrien and Baeyens, 2017). Hip and knee extension strength are strongly associated with vertical jump performance, whereas ankle plantar flexion strength is not well associated (Tsiokanos et al., 2002). From a muscle morphology perspective, lower limb motor performance has been shown to be strongly related to proximal muscles and more weakly related to distal muscles (Ema et al., 2018; Miller et al., 2021). Even in the shot put, which is literally "putting" by push type PD sequence of the upper limb, its performance is correlated with bench press 1RM (Terzis et al., 2007), and training the upper-limb proximal muscles, such as the pectoralis major, is emphasised by shot putters.
However, as humans are bipedal, the upper limb is free from the mechanical load associated with daily body support like the lower limb (Glasheen & McMahon, 1995). Recently, Hashimoto et al. (2023) showed that the cross-sectional area of the distal palmar flexor muscles was most strongly associated with the season best record in shot putters ($r > 0.9$) among that of trunk and upper limb muscles, which differs from lower limb muscularity in athletes. Thus, the findings from the lower limb may not be directly applicable to the upper limb of the shot putter. Previous studies on the shot-put motion (Błażkiewicz et al., 2019; Landolsi et al., 2018) have shown that peak power throughout the arm is correlated with performance, but that maximum energy tends to occur at the hip joint and is lost in the upper limb. However, the kinetic demands of each upper limb joint during the shot-put motion for shot put performance have not been investigated in detail.
The purpose of this study was to clarify the relationship between the upper limb joint kinetics and the flight distance in the shot put. We hypothesized that the distal wrist kinetic exertion is associated with the flight distance.

METHODS: The *a priori* power analysis (correlation analysis: $\alpha = 0.05$, $1-\beta = 0.80$, $|\rho| = 0.70$) indicated that the required sample size was 11. We recruited 13 male shot putters (mean ± SD, age: 21.8 ± 3.4 years, height: 177.5 ± 5.2 cm, weight: 103.8 ± 19.2 kg, personal best (PB): 15.26 ± 2.40 m [range: 11.47–18.85 m], season best (SB): 14.97 ± 2.54 [range: 9.77–18.53 m]), all using the rotational technique. The experimental procedure was approved by the Human Research Ethics Committee at University of Tsukuba (reference number: PE021-140).

Participants performed shot put trials, as if they were in a competition, on a temporary indoor shot-put circle. They put the shot towards a protective net. We used a standard male indoor shot with six reflective hemispherical markers, 14 mm diameter. The measurement procedure using cluster and calibration markers was executed similar to Sado et al. (2020). Additional hemispherical markers,14 mm in diameter, were attached on the right third metacarpal head and middle fingertip. In addition, bilateral dynamic functional trials for the shoulder and elbow joints were performed. Shot-put trials were repeated up to 8 times, with sufficient rest between trials (>3 min), until data were successfully obtained, and the participant completed three trials with a self-rated score of 3 or higher on a 5-point scale. The 3D position coordinates of the reflective markers were recorded using a 26-camera motion capture system (Vicon-MX, Vicon motion systems Ltd., UK, 250 Hz).

The position coordinates of the reflective markers were smoothed using a Butterworth low-pass digital filter with a cut-off frequency of 10–13 Hz, determined using residual analysis (Winter, 2009). The shot centre was estimated using the least squares method for the six markers on the shot surface. We analysed the release phase from the instant the shot left the neck to the instant the shot left the hand. Each of these two instants was defined as the frame in which the distance between the cervicothoracic joint and the shot centre or between the fingertip and the shot centre exceeded 2 SDs of the mean distance.

We calculated shot velocity and acceleration by first- and second-order time derivatives of the shot centre position. Shot force and power were calculated as the product of shot mass and acceleration, and the dot product of shot force and velocity, respectively. We estimated the flight distances using the equation of projective motion and the shot release parameters.

The segment centre of mass (COM) and inertial parameters were calculated using scaling estimation equations (Dumas et al., 2007). We used inverse dynamics to calculate joint torque, which was transformed into joint coordinate system. Specifically for the shoulder joint, horizontal adduction/abduction is the $\boldsymbol{x}$-axis, internal/external rotation is the $\boldsymbol{z}$-axis, and the cross product of both axes is the $\boldsymbol{y}$-axis. For the hand-shot system, we developed a Euler equation of motion around the hand-shot system COM as shown below:

$$\dot{\boldsymbol{L}} = \boldsymbol{r}_{\overline{\mathbf{CoM-Wrist}}} \times \boldsymbol{F}_{\mathbf{Wrist}} + \boldsymbol{\tau}_{\mathbf{Wrist}}, \quad (1)$$

$$\boldsymbol{L} = \sum_{i=1}^{2} (\boldsymbol{L}_i + \boldsymbol{r}_{\overline{\mathbf{CoM-}i}} \times m_i \dot{\boldsymbol{r}}_{\overline{\mathbf{CoM-}i}}). \quad (2)$$

where $\boldsymbol{L}$ is the angular momentum of the hand-shot system, $\boldsymbol{r}$ is the relative position vector from the composite COM of the shot and hand to the joint or segment COM, $\boldsymbol{F}$ and $\boldsymbol{\tau}$ are joint force and torque respectively. i=1,2 shows the shot or hand. Joint power was calculated as the dot product of joint torque and angular velocity.

The Shapiro-Wilk test was used to confirm the normality of the distribution of the analysed variables. If the normality was confirmed, the Pearson's product-moment correlation coefficient (*r*) was used, otherwise Spearman's rank correlation coefficient (*ρ*) was used to assess correlation between the flight distance and peak norm of torque or peak power. The significance level was set at $\alpha = 0.05$.

RESULTS: The flight distance was 12.96 ± 1.99 m. Shot force and power peaked at 37 ± 7% and 44 ± 10%-time segment of the release phase, respectively (Figure 1).

The wrist and shoulder joints exerted palmar flexion and horizontal adduction torques during the release phase (Figure 2AC), with similar patterns to the shot force. The wrist and shoulder joints generated powers during approximately 50–100% time segment of the release phase (Figure 2DF). Meanwhile, the elbow joint exerted the flexion torque (Figure 2B) and absorbed power (Figure 2E).

Peak norms of wrist and shoulder torque (63.70 ± 16.79 and 151.39 ± 31.29 Nm) correlated significantly with the flight distance (*r* or *ρ* > 0.70, *p* < 0.01), but that of elbow torque did not

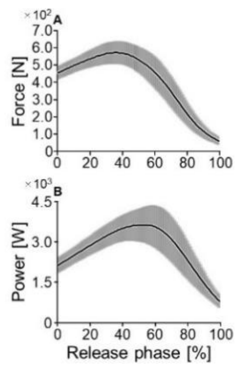

Figure 1 Ensemble averages of the norm of shot force (A) and power (B).

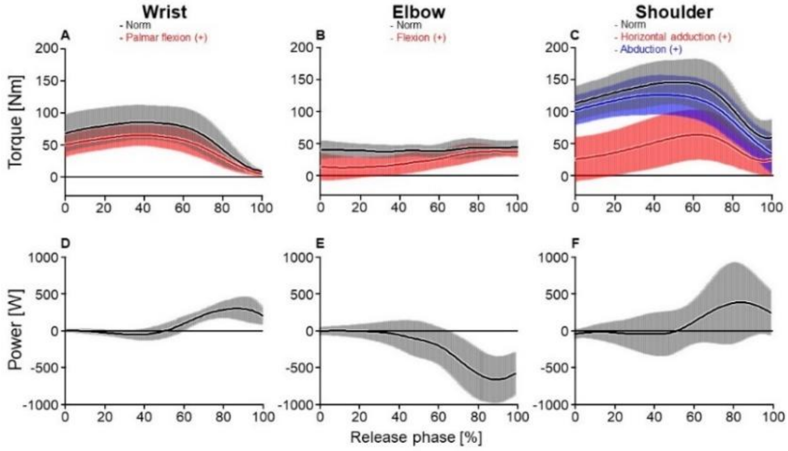

Figure 2 Ensemble averages of the joint torque (A–C) and power (D–F).

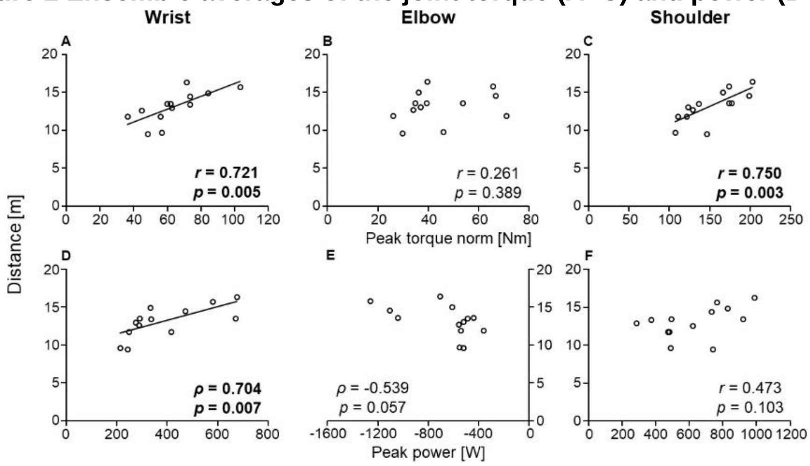

Figure 3 Correlation of shot flight distance with peak torque (A–C) and peak power (D–F).
Negative peak value only at elbow power (E)

(r = 0.26, p = 0.39) (Figure 3A-C). Only wrist peak power (385.17 ± 155.49 W) correlated significantly with the flight distance (r = 0.70, p < 0.01) (Figure 3D), while the others did not ((|r| or |ρ| < 0.55, p > 0.05) (Figure 3EF).

DISCUSSION: We found that the wrist torque and power were strongly associated with the flight distance This supported the hypothesis. A previous muscle morphology study (Hashimoto et al., 2023) have reported that the distal muscles of the upper limb were developed in shot putters and strongly associated with the shot put performance, which differs from the lower limbs. By analysing an actual shot-put motion, we provide the evidence supporting the importance of the upper-limb distal part, and further add the musculoskeletal demands for the wrist joint as a power generator, too. This finding suggest that athletes and their coaches should strengthen the palmar flexors at the wrist to improve performance. However, the personal records of the athletes in this study range from 11.47 to 18.85 m. Therefore, the linear relationship obtained in this study may not be directly applicable to world class athletes.

Shoulder torque was associated with the flight distance, but shoulder power was not. This suggests that the important kinetic role of the shoulder joint for higher performance is to transfer the mechanical power generated by the trunk and lower limbs, rather than to generate power directly Powers at the shoulder and wrist peaked almost simultaneously rather than sequentially. Thus, the PD sequence in the shot-put motion might not be achieved by the shoulder power generation, but by the shoulder power transfer. To examine this mechanism in detail, the shoulder power exerted on each thorax and upper limb (segment torque power) might be needed, which is a future theme.

Elbow joint exerted flexion torque, even though shot put motion is exerted by upper limb push type PD sequence. Regarding the elbow joint applying flexion torque, considering the release phase, the athlete accelerates while rotating and finally looks back to release the projectile.

Therefore, it is assumed that the elbow joint applies flexion torque to suppress the elbow extension due to the centrifugal force applied when looking back and to convert the shot into a straight trajectory. Van Ingen Schenau et al. (1994) found that in tasks involving postural control, such as pushing an object, the biarticular muscles provide postural control by simultaneously flexing one joint during the extension. However, we did not analyse the muscle activity and could not discuss each muscle function in this study. This is a future theme.

CONCLUSION: We found the strong correlation of wrist torque and power with flight distance by analysing the actual shot-put motion. We suggest that it is important for athletes and their coaches to strengthen the musculoskeletal function around the distal wrist joint rather than the proximal joint. For the shoulder joint, only peak torque was associated with flight distance, suggesting that the role of the shoulder is specialised for torque exertion. These findings suggest that training the wrist palm flexors and training around the shoulder joint with an emphasis on torque exertion ability rather than power capacity may be beneficial. However, these suggestions may not be directly applicable to athletes of different ability levels than those who participated in this study. We open a novel perspective for training strategies to maximize upper limb motor performance.

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ACKNOWLEDGEMENTS: This work was supported by JSPS KAKENHI (21K17592) and Mizuno Sports Promotion Foundation (2023) to N.S.