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Effect of external work magnitude on mechanical efficiency of sledge jumping

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Running title: Mechanical efficiency during sledge jump

Abstract

The mechanical efficiency of human locomotion has been studied extensively. The mechanical efficiency of the whole body occasionally exceeds muscle efficiency during bouncing type gaits. It is thought to occur due to elasticity and stiffness of the tendinomuscular system and neuromuscular functions, especially stretch reflexes. In addition, the lower limb joint kinetics affect mechanical efficiency. We investigated the impact of varying external work on mechanical efficiency and lower limb kinetics during repeated sledge jumping. Fifteen male runners performed sledge jumping for 4 min at three different sledge inclinations. Lower limb kinematics, ground reaction forces, and expired gases were analyzed. Mechanical efficiency did not differ according to sledge inclination. Mechanical efficiency correlated positively with the positive mechanical work of the knee and hip joints and the negative contribution of the hip joints. Conversely, it correlated negatively with both the positive and negative contributions of the ankle joint. This may be attributable to the greater workload in this study versus previous studies. To achieve greater external work, producing more mechanical energy at the proximal joint and transferring it to the distal joint could be an effective strategy for improving mechanical efficiency because of the greater force-generating capability of distal joint muscles.

Keywords: energy expenditure, joint work, lower extremity, sledge track inclination

Word Count: 3364

Introduction

Mechanical efficiency in human locomotion has been studied extensively in terms of physiology, which is defined as mechanical work divided by energy expenditure[1,2]. Muscle efficiency of concentric action is approximately 25–30% [3], while the whole-body mechanical efficiency occasionally exceeds the muscle efficiency [2]. Studies [1,2] have suggested that an elastic mechanism would improve mechanical efficiency during bouncing gait, a suggestion derived from the spring-mass model. Furthermore, preactivity of the lower extremity muscles is assumed to increase the sensitivity of the muscle spindle via enhanced alpha-gamma-coactivation potentiating stretch reflexes [4], enhancing tendinomuscular stiffness [5,6] and, consequently, the economy of running[7]. However, [8] indicated that the lower limb joints each have different mechanical efficiency. This suggests that other factors improve the whole-body mechanical efficiency in bouncing type gaits.

However, it is not easy to measure the mechanical efficiency of each factor during exercise directly. One study [9] compared energy cost, which is an inverse of mechanical efficiency, and lower limb biomechanics during repeated vertical jumping across different exercise conditions. The energy cost was lower when the ankle joint did most of the required mechanical work, as opposed to compensating for the lack of ankle joint involvement by the knee and hip joints in repeated vertical jumping [9]. This also suggests variation in mechanical efficiency among the lower limb joints [8]. Therefore, the only option was to compare mechanical efficiency under different exercise conditions within the same subject and speculate on the relationship between mechanical efficiency and biomechanical factors.

Repeated jumping is well suited to exploring the impact of biomechanical factors on mechanical efficiency because it is a simple exercise and it is easy to measure physiological and biomechanical variables simultaneously. However, the vertical jump has limited ability to create varied conditions. Sledge jumping, a form of repeated jumping, has become a widely accepted model in sport science [10–12]. Since the 1980s, a sledge apparatus has been used to evaluate mechanical efficiency in stretch-shortening cycle (SSC) actions [13–15]. It enables the separation of positive and negative work [16] and provides control over jumping frequency, dropping, and jumping heights [17], which is difficult during conventional vertical jumping. Sledge jumping studies have revealed that a greater pre-stretch intensity and shorter coupling time improve mechanical efficiency [15,18]. Moreover, the inclination of the sliding track can be adjusted, allowing the regulation of external work demands during repeated jumping without altering the dropping and jumping displacements. Maintaining the positional relationship between the sledge, force platform, and participants is unified; different sliding track inclinations elucidate kinetic adaptation on different exercise conditions.

In the present study, the influence of external work magnitude on mechanical efficiency and lower limb kinetics were investigated during repeated sledge jumping. In accordance with mechanical principles, a steeper sliding track inclination increases external work when sledge displacement remains constant. We hypothesized that a steeper inclination would increase energy expenditure and mechanical efficiency because the mechanical work contribution of the lower limb joints would change with the external work demand.

Methods

Participants: The participants included 15 male Japanese middle- and long-distance runners (age: 20.5 ± 1.0 years, height: 1.72 ± 0.05 m, body mass: 58.1 ± 4.8 kg). The participants were enrolled from university track and field clubs and provided voluntary informed consent prior to participation. This study was approved by the Ethical Committee of the College of Humanities and Sciences, Nihon University, Japan (approval number 03-29), and was conducted in accordance with the Declaration of Helsinki.

Procedure and measurements: Before measurements, each participant warmed-up for 10–30 min as preferred, such as by jogging. The study involved participants performing three bouts of sledge jumping for 4 min. Each bout was set a different sledge inclinations. All measurements were performed on the same day. Measurements were conducted using a sledge apparatus (Takei Scientific Instruments, Tokyo, Japan; Figure 1) [13] including a sledge (mass: 27.4 kg), a sliding track, and a force platform (Type 9281B, Kistler Instruments, Winterthur, Switzerland) positioned perpendicular to the sliding track surface. The sliding track inclinations used were 18.5°, 23.0°, and 27.5° relative to the horizontal. The order of trials was randomized. The participants had at least a 5-min rest between trials. Participants jumped once every 5 s, with an assistant releasing the sledge at the same interval from a predetermined height. Participants jumped immediately after landing on the force platform, reached the predetermined height, and the assistant caught and held the sledge until the next release. A 4 min exercise duration was chosen to attain a steady-state level of oxygen consumption ($\dot{V}O_2$). As a result, each participant performed 48 jumps at each sledge inclination. Both the drop and jump heights were set at 50% of the maximum jump height achieved at a 23.0° sledge inclination.

During the measurements, ground reaction forces (GRF) were measured at a frequency of 1 kHz using the aforementioned force platform. Kinematic data for the right half of the body were captured using a motion capture system (Vicon Vero v2.2, Vicon Motion Systems, Oxford, UK) at a rate of 250 Hz. Reflective markers were attached to anatomical landmarks (toe, fifth metatarsal bone, heel, lateral malleolus, lateral condyle, greater trochanter, and shoulder), the sledge, and the two cluster markers (shank and thigh). Kinematic and GRF data were synchronized using Vicon Nexus software (Vicon Motion Systems, Oxford, UK). $\dot{V}O_2$, $\dot{V}$CO2, and R were continuously analyzed using the "breath-by-breath" method with a computerized standard open-circuit technique [19] (AE301s, Minato Medical Science, Osaka, Japan).

Data analysis: We focused our analysis on the sagittal plane due to the sliding track's inclination in this plane. Two-dimensional coordinates within the sagittal plane and GRF data were smoothed using a Butterworth low-pass filter at 10 Hz [20]. To determine positive and negative external work, we integrated the inner product of the GRF and the velocity of the sledge seat using a fourth order Runge–Kutta method. $\dot{V}O_2$, $\dot{V}$CO2, and R were recorded during the final minute of each 4 min exercise period. Energy expenditure was computed using the energy equivalent of 20,202 $J \cdot L^{-1}$ of oxygen, based on a respiratory exchange ratio (R) of 0.82. This equivalence allowed for a ±0.01 R change to correspond with a ±50 J change in energy expenditure [9,21]. Mechanical efficiency (gross efficiency) was calculated by dividing the positive external mechanical work by energy expenditure [22].

The center of mass and moment of inertia for the foot, shank, and thigh segments were estimated following previously reported methods [23]. Joint torques at the hip, knee, and ankle were determined using an inverse dynamics approach (Eq. 1–2) [9]

$$ma = mg + F_d + F_p \qquad \text{(Eq. 1)}$$

$$I\alpha = r_d \times F_d + r_p \times F_p + T_d + T_p \qquad \text{(Eq. 2)}$$

where, m is the mass of the segment, a is the acceleration of the segment's center of mass, g is the gravitational acceleration, F_d is the reaction force at the distal end of segment, F_p is the reaction force at the proximal end of segment, I is the moment of inertia of the segment, α is the angular acceleration of the segment, r_d is the moment arm of F_d, r_p is the moment arm of F_p, T_d is the joint torque acting on the segment at distal joint, and T_p is the joint torque acting on the segment at proximal joint. Joint power was determined as the inner product of joint torque and joint angular velocity. Mechanical work was computed by integrating the joint power using a fourth order Runge–Kutta method. To assess the relative contribution of each lower-limb joint to the total positive and negative mechanical work, we divided the total positive or negative mechanical work by the corresponding joint's mechanical work. Biomechanical data were averaged over the contact phase of five continuous jumps from each sledge inclination. These jumps were selected from the final 1 min of each 4 min period.

Statistical analysis: We determined the required number of participants using G*Power (version 3.1.9.6), which indicated that a minimum of 15 participants were needed ($\alpha = 0.05$, $1-\beta = 0.9$, partial $\eta^2 = 0.25$). The results are presented as means ± standard deviations (SD). Prior to the analysis, the normality of variables was assessed using the Shapiro-Wilk test. Pearson's correlation coefficient was used to determine the correlation of mechanical efficiency with mechanical work. To analyze the main effects of sliding track inclination, we used one-way analysis of variance (ANOVA) for repeated. Homogeneity of variance was assessed using Mauchly's test of sphericity, adjusting degrees of freedom if sphericity was not met before performing the F-test. If significant main effects were observed, multiple analyses were performed using the Bonferroni method to analyze differences between inclinations. Statistical analyses for 0D parameters were performed using SPSS version 28.0 for Mac (IBM Corp, Armonk, NY, USA). For 1D parameters (joint angular velocity, torque, and joint power curves), the Statistical Parametric Mapping (SPM) technique [24] on MATLAB R2023a (MathWorks Inc., Natick, MA, USA) was used with the open-source SPM code (www.spm1d.org). The statistical significance level was set at 5%. In addition, we calculated partial η^2 effect sizes for ANOVA for 0D parameters and interpreted η_p^2 as follows: trivial ($\eta_p^2 < 0.01$), small ($0.01 \leq \eta_p^2 < 0.06$), medium ($0.06 \leq \eta_p^2 < 0.14$), and large ($0.14 \leq \eta_p^2$) [25].

Results

No significant differences were observed in sledge displacement, contact time, or mechanical efficiency among the studied conditions (Table 1). However, significant differences were observed in $\dot{V}O_2$, energy expenditure, and external work across the conditions, with the smallest and greatest inclination of 18.5° and 27.5°, respectively (Table 1). The positive contribution of the hip joint was significantly greater at 27.5° than at 23.0° and 18.5°, but the other joint contributions did not differ between the conditions (Table 1).

Table 2 demonstrates the correlation coefficients between mechanical efficiency and joint mechanical work, and contribution. Mechanical efficiency was positively correlated with the positive mechanical work of the knee and hip joints and both positive and negative contributions of the ankle joint, and negative contribution of the hip joint.

Figure 2 illustrates the results of ANOVA of the positive and negative joint mechanical work of the ankle, knee, and hip joints during the contact phase. The mechanical work differed significantly across conditions, with the lowest value observed at the 18.5° inclination and the greatest at 27.5° ($0.645 \leq \eta_p^2 \leq 0.793$).

Figure 3 shows the average patterns for the angles, torques, and powers for the ankle, knee, and hip joints during the contact phase in each inclination, along with the results of ANOVA. Joint angular velocity of the ankle, knee, and hip joints exhibited significant differences, particularly near the maximum and minimum values between the different conditions. Ankle and knee joint torques were significantly greater at steeper inclinations around the midpoint of the contact phase, corresponding to the moment of maximum torque. The hip joint torque also significantly increased at steeper inclinations during the latter half of the contact phase. In addition, the ankle joint power had significantly greater negative and positive peak values at steeper inclinations. Knee joint power differed significantly throughout most of the contact phase, except for the middle phase when the power transitioned from negative to positive values. The hip joint power was significantly higher at steeper inclinations during the latter half of the contact phase.

Discussion

The present study was the first to explore the relationship between lower limb kinetics and mechanical efficiency during repeated sledge jumping. We found that the energy expenditure varied significantly among inclinations, with a higher value at 27.5° and a lower value at 18.5°. Mechanical efficiency did not differ among different sledge inclinations. Positive mechanical work of the knee and hip joints was positively correlated with mechanical efficiency. The results also revealed that positive and negative contributions of mechanical work produced by the ankle joint had negative correlations with mechanical efficiency, while a negative contribution of mechanical work of the hip joint was positively correlated with mechanical efficiency. Therefore, our hypothesis was partly rejected by comparing inclinations but partly supported by correlations with mechanical efficiency.

Energy expenditure and mechanical work were significantly higher at 27.5° inclination and significantly lower at 18.5°, which constituted responses to external work demand. A steeper inclination has a greater external work demand and vice versa. Although the resultant displacement of dropping and jumping did not differ across inclinations, steeper inclinations resulted in higher dropping and jumping heights. The changes in energy expenditure were exactly as we had expected. However, there were no significant differences among inclinations, although the mean mechanical efficiency was slightly higher at steeper inclinations, in which its effect size was large. We hypothesized that a steeper inclination indicates higher mechanical efficiency because the SSC action of the leg extensors would be enhanced. Maximal dorsiflexion and knee flexion velocities were significantly higher at steeper inclinations, indicating increased pre-stretch velocity of the leg extensor muscles. Greater negative mechanical work of the ankle, knee, and hip joints at steeper inclinations further supported the idea of heightened pre-stretch intensity. However, there was no significant difference in mechanical efficiency among the studied conditions. One possible explanation is that of the contact time of sledge jumping, which was quite long (approximately 0.7 s), suggesting that isolated eccentric and concentric actions occurred during the contact phase instead of full SSC actions. There is a possibility of prolonged contact time due to a high workload. The sledge weighed 27.4 kg and was approximately 50% of the participants' body mass. Some jumping studies showed that a greater load induced a longer contact time [26,27]. Additionally, the muscle strength of our participants might not be great as they were distance runners. Therefore, the effect of SSC actions on mechanical efficiency of the knee and ankle joints at steeper inclinations may be limited.

Significant correlations between mechanical efficiency and some mechanical work variables were found. The positive contribution of the ankle joint was correlated negatively with mechanical efficiency, which is opposite to our hypothesis. [8] reported that the lower limb joints exhibit varying mechanical efficiency, and that the ankle joint has greater mechanical efficiency. Changes in joint contributions may lead to differences in whole-body mechanical efficiency. In the present study, all joint mechanical work significantly increased with inclination. The positive contribution of the hip joint was significantly greater at the steepest inclination. In addition, the positive and negative contributions of the ankle joint were negatively correlated, whereas negative contributions of the hip joints were positively correlated, with mechanical efficiency. The contrasts with a previous study [28] comparing the whole-body mechanical efficiency of walking and running, which showed that the ankle joint has greater mechanical efficiency. Another study [9] investigated the relationship between energy cost and joint work contributions during repeated vertical jumping, and found that greater mechanical work by the ankle joint was associated with lower energy cost, which means greater mechanical efficiency, while greater knee joint work was associated with higher energy cost. Perhaps proximal joints produce mechanical work less efficiently than distal joints [8,29]. However, we found that greater mechanical efficiency may be associated with a smaller contribution of the ankle joint and greater mechanical work of the hip and knee joints, despite the conventional understanding that proximal joints are less efficient. This discrepancy may be attributable to differences in workload. [28] studied jogging at speeds of 2.0–3.25 m/s, which was considered a low workload. Comparing mechanical work between our study and the previous jumping study [9], the workload per jump in our study was approximately 1.5–2.0 times greater. This implies that the workload of one jump in our study was markedly higher due to the inclusion of body weight and the sledge, which weighed 27.4 kg and accounted for approximately 50% of participants' body mass. Previous studies [30,31] of vertical jumping have reported that joint contributions to mechanical work change with jump height, reflecting varying workload. Therefore, it is reasonable to conclude that workload affects lower limb joint contribution and the strategy for maximizing mechanical efficiency, with proximal joints contributing more mechanical work in situations involving higher workloads.

The observed inconsistency in joint mechanical work (or contribution) and mechanical efficiency may be explained by the role of biarticular muscles, such as the gastrocnemius muscle, which act as both plantarflexors and knee flexors. These muscles may play a role in reducing energy costs [32]. They are capable of bidirectionally transferring mechanical energy between the knee and ankle joints. When the knee joint flexes and the ankle joint dorsiflexes simultaneously, mechanical energy may transfer from the ankle to the knee joint [33]. Conversely, when the knee joint extends and the ankle joint plantarflexes, mechanical energy transfers from the knee to the ankle joint [33]. During the latter scenario, the gastrocnemius muscle generates negative power at the knee joint and positive power at the ankle joint, facilitating the transfer of mechanical energy from the knee to the ankle joint [33]. In the present study, the plantarflexion torque during almost the entire contact time was significantly greater at inclinations of 23.0° and 27.5° compared to 18.5°. This suggests that the contribution of the gastrocnemius muscle to plantarflexion torque was greater at steeper inclinations. Similarly, the knee flexion torque generated by the gastrocnemius muscle was also greater at steeper inclinations, although the net knee joint torque indicated extension. This indicates that energy transfer from the knee to the ankle joint might be more substantial during the latter part of the contact phase at steeper inclinations. The knee joint power at steeper inclinations was significantly higher from the onset of positive power, approaching its maximum value in the latter half of the ground contact. However, the difference in its maximum value was relatively small compared to that of the ankle joint. This suggests that the transfer of energy from the knee to the ankle joint was more pronounced at steeper inclinations. The lack of significant differences in mechanical efficiency might be due to energy transfer in the biarticular muscles offsetting the greater contribution of metabolically expensive joints. Nonetheless, the amount of energy transferred from the knee to the ankle joint may not exceed the mechanical energy generated at the ankle joint [33]. In addition, proximal joints, while metabolically expensive, can generate greater force and power due to muscles with longer fibers [29]. Therefore, the mechanisms underlying mechanical efficiency are complex and may be related to the exercise workload.

There were several limitations to the present study. First, while the external work demand was controlled using sliding track inclination, it still exceeded the demands of normal repeated vertical jumping because the mass of the sledge was approximately 50% of participants' body mass. Second, the participants in this study were all male runners. Sex differences in muscle strength may affect the findings as the sledge mass might account for a substantial proportion of their body mass. Third, the discussion of biarticular muscle action remains speculative [33], as biarticular muscle action was not measure directly, such as with ultrasound. However, this study is the first attempt to examine joint kinetics during sledge jumping, providing valuable insights into the biomechanics behind mechanical efficiency. Fourth, we examined gross efficiency, including the basal metabolic rate. One of the criticisms of gross efficiency is the basal metabolic rate. When the mechanical work increases, the contribution of the basal metabolic rate may decrease, which might lead to an increase in gross efficiency [22]. On the other hand, energy cost, an inverse of gross efficiency, is related to endurance performance[34], and the relationship between energy cost and gross efficiency is discussed[1,35]. Therefore, gross efficiency would be suitable when considering endurance performance of humans. Finally, this study had a small sample size. Some variables may have had an effect, but none were significant. The statistical power to detect small effect sizes was relatively low.

The present study explored the relationship between mechanical efficiency and lower limb kinetics during repeated sledge jumping at different sliding track inclinations. Mechanical efficiency significantly correlated positively with the mechanical work of the knee and hip joints and negatively with the contribution of the ankle joint. This may be attributable to the greater workload in this study vs other studies. To achieve greater external work, producing more mechanical energy at the proximal joint and transferring it to the distal joint could be an effective strategy for improving mechanical efficiency because of the greater force-generating capability of distal joint muscles.

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Figure Captions

Figure 1—Schematic illustration of the sledge apparatus. A, Participant; B, Sledge; C, Sliding track; D, Force platform (Type 9281B, Kistler Instruments, Winterthur, Switzerland); E, Assistant; θ, Sliding track inclination.

Figure 2—Mean (±SD) mechanical work of the ankle, knee, and hip joints during the contact phase, along with the results of ANOVA.

Figure 3—Mean (±SD) joint angles (a: ankle, b: knee, c: hip), torques (d: ankle, e: knee, f: hip), and powers (g: ankle, h: knee, i: hip) during the contact phase and results of SPM ANOVA. Blue, red, and yellow lines indicate significant differences between 18.5° and 23.0°, between 23.0° and 27.5°, and between 18.5° and 27.5°, respectively.

Table 1 Mean (±SD) and one-way ANOVA results of the selected parameters studied in the three different inclination conditions.

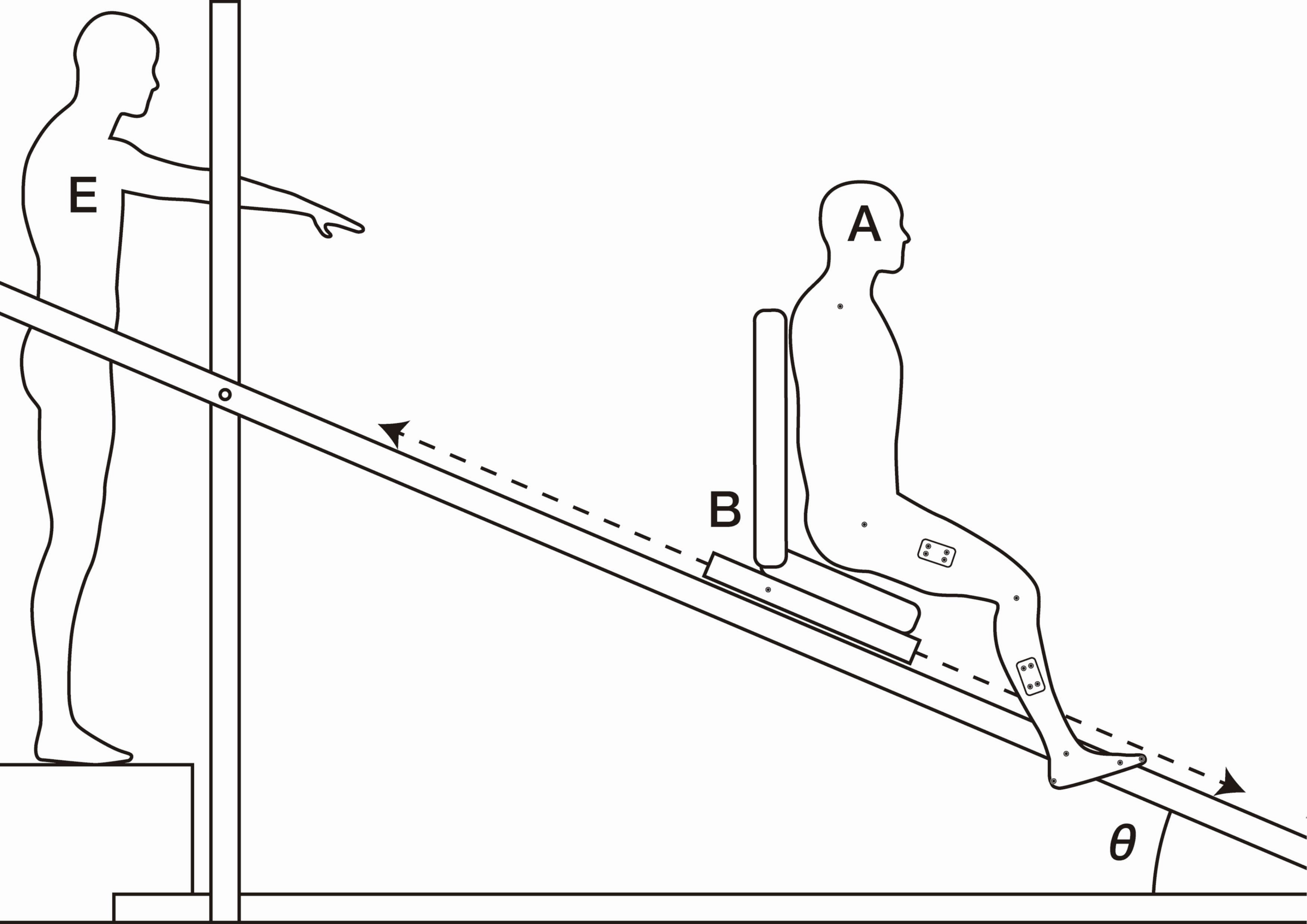
Variable	18.5º	23.0º	27.5º	F	Partial η^2	Multiple comparison
External work$^+$ (J·kg^{-1})	3.51±0.63	4.29±0.76	5.21±0.81	84.75*	0.858	18.5º<23.0º<27.5º
External work$^-$ (J·kg^{-1})	−2.69±0.44	−3.31±0.52	−4.03±0.53	242.16*	0.945	27.5º<23.0º<18.5º
Sledge displacement (m)	0.66±0.11	0.66±0.12	0.69±0.10	2.36	0.144	
Contact time (ms)	739±135	702±154	713±121	1.59	0.102	
$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	13.7±3.3	15.3±3.3	18.1±3.2	50.10*	0.782	18.5º<23.0º<27.5º
Energy expenditure (J·kg^{-1}·jump^{-1})	23.2±5.7	25.8±5.6	30.5±5.5	47.95*	0.774	18.5º<23.0º<27.5º
Mechanical efficiency (%)	15.8±4.4	16.9±2.8	17.4±3.5	2.91	0.172	
Ankle contribution+ (%)	37.7±3.7	36.8±9.1	35.3±8.6	2.54	0.154	
Knee contribution+ (%)	44.8±7.1	44.3±6.3	43.3±6.1	0.60	0.041	
Hip contribution+ (%)	17.5±4.7	18.8±4.8	21.3±4.1	9.23*	0.397	18.5°, 23.0°<27.5°
Ankle contribution− (%)	27.2±10.2	25.5±8.5	24.8±8.9	2.35	0.144	
Knee contribution− (%)	59.0±8.6	60.1±8.0	59.6±7.7	0.28	0.020	
Hip contribution− (%)	13.8±5.8	14.4±6.3	15.5±5.4	2.01	0.126	

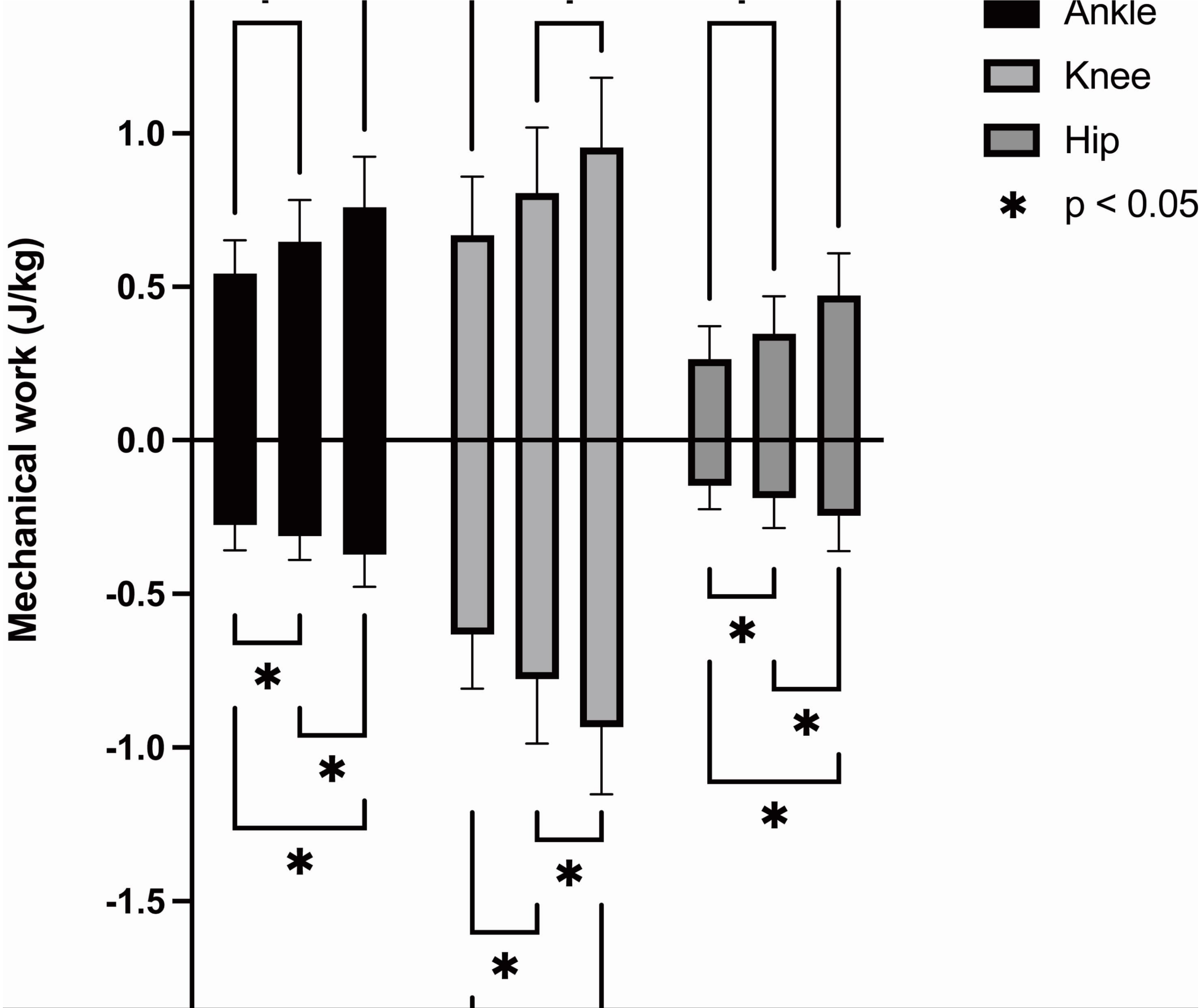
*: $p < 0.05$

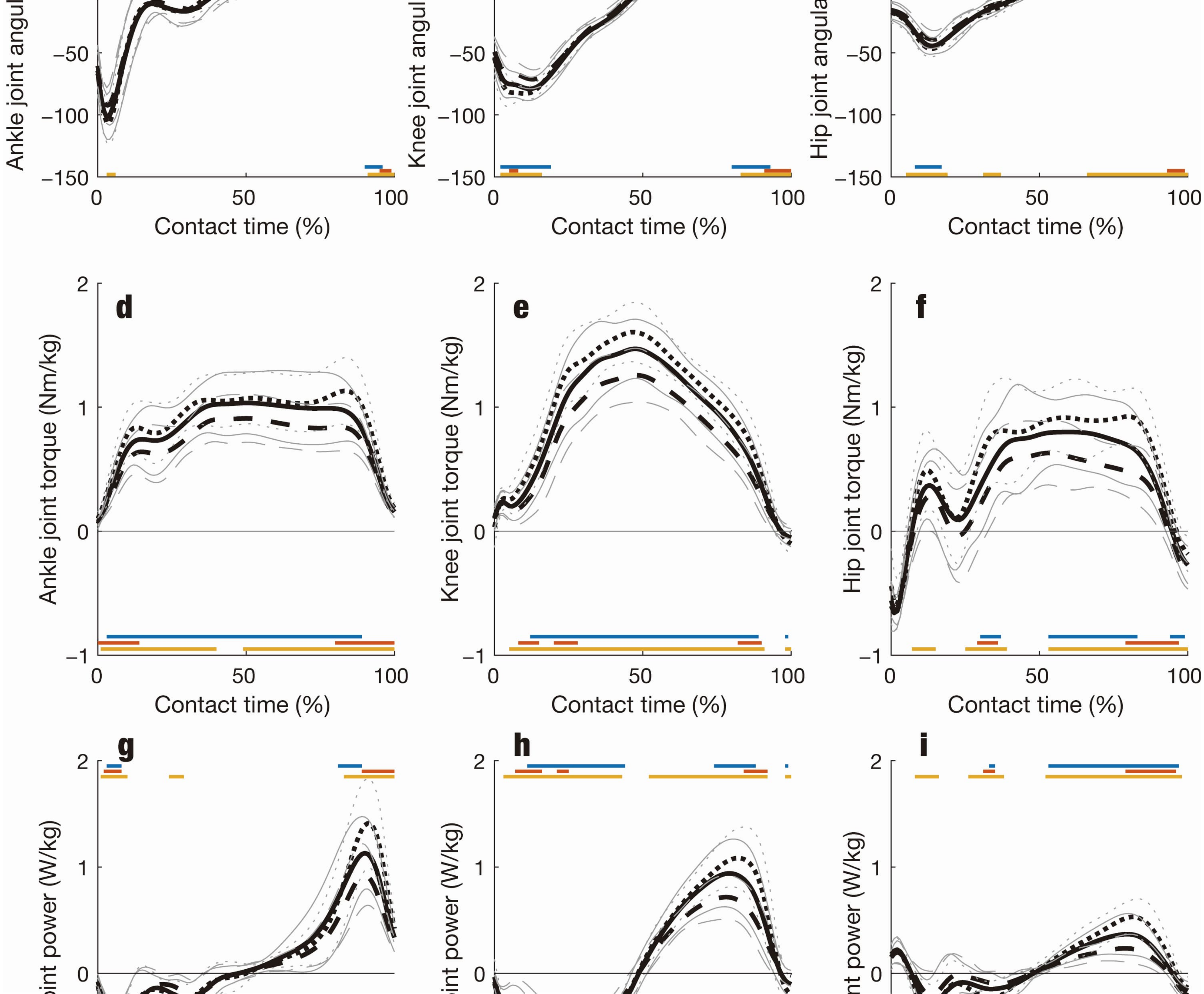
Table 2 Selected parameters correlation coefficient with energy expenditure (n = 15, number of trials = 45).

Variable	Energy expenditure	Mechanical efficiency
Ankle positive mechanical work	0.50*	0.09
Knee positive mechanical work	0.45*	0.43*
Hip positive mechanical work	0.46*	0.38*
Ankle negative mechanical work	−0.31*	0.10
Knee negative mechanical work	−0.62*	−0.12
Hip negative mechanical work	−0.30*	−0.42
Ankle positive contribution	−0.08	−0.35*
Knee positive contribution	−0.07	0.27
Hip positive contribution	0.24	0.28
Ankle negative contribution	−0.20	−0.30*
Knee negative contribution	0.21	0.01
Hip negative contribution	0.02	0.43*

*: $p < 0.05$


E
A
B
θ


Mechanical work (J/kg)
1.0
0.5
0.0
-0.5
-1.0
-1.5
Ankle
Knee
Hip
* p < 0.05


Ankle joint angul
−50
−100
−150
0
50
100
Contact time (%)
Knee joint angul
−50
−100
−150
0
50
100
Contact time (%)
Hip joint angula
−50
−100
−150
0
50
100
Contact time (%)
d
Ankle joint torque (Nm/kg)
2
1
0
−1
0
50
100
Contact time (%)
e
Knee joint torque (Nm/kg)
2
1
0
−1
0
50
100
Contact time (%)
f
Hip joint torque (Nm/kg)
2
1
0
−1
0
50
100
Contact time (%)
g
oint power (W/kg)
2
1
0
h
int power (W/kg)
2
1
0
i
nt power (W/kg)
2
1
0