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RESEARCH ARTICLE

External mechanical work done during the acceleration stage of maximal sprint running and its association with running performance

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ABSTRACT

This study aimed to elucidate how external mechanical work done during maximal acceleration sprint running changes with increasing running velocity and is associated with running performance. In twelve young males, work done at each step over 50 m from the start was calculated from mechanical energy changes in horizontal anterior–posterior and vertical directions and was divided into braking ($-W_{kap}$ and $-W_v$, respectively) and propulsive ($+W_{kap}$ and $+W_v$, respectively) phases. The maximal running velocity (V_{max}) appeared at 35.87±7.76 m and the time required to run 50 m ($T_{50\,m}$) was 7.11±0.54 s. At 80% V_{max} or higher, $+W_{kap}$ largely decreased and $-W_{kap}$ abruptly increased. The change in the difference between $+W_{kap}$ and $|-W_{kap}|$ (ΔW_{kap}) at every step was relatively small at 70% V_{max} or lower. Total work done over 50 m was 82.4±7.5 J kg^{-1} for $+W_{kap}$, 36.2±4.4 J kg^{-1} for $|-W_{kap}|$, 14.3±1.9 J kg^{-1} for $+W_v$, and 10.4±1.2 J kg^{-1} for $|-W_v|$. The total ΔW_{kap} over 50 m was more strongly correlated with $T_{50\,m}$ (r=−0.946, P<0.0001) than the corresponding associations for the other work variables. These results indicate that in maximal sprint running over 50 m, work done during the propulsive phase in the horizontal anterior–posterior direction accounts for the majority of the total external work done during the acceleration stage, and maximizing it while suppressing work done during the braking phase is essential to achieve a high running performance.

KEY WORDS: 50 m force plate system, Ground reaction force, Propulsive and braking phases, Positive and negative work

INTRODUCTION

Among human locomotive movements, sprint running is the most powerful. The mechanical power output during sprint running reaches about 3000 W step^{-1} in sprinters (Fukunaga et al., 1981). Sprint running from a stationary state inevitably involves a period of time until the running velocity reaches the maximum, i.e. the acceleration stage. In this stage, runners are required to maximally accelerate their bodies to attain a high running velocity within a short period. Thus, examining the mechanics of the acceleration stage of maximal sprint running is essential to elucidate how runners are capable of achieving a high power movement. To realize this, it is necessary to continuously obtain data on kinetics and/or kinematics at each step during the entire period of maximal sprint running from the start of the run, because these markedly vary with increasing running velocity (Nagahara et al., 2014, 2018a,b,c). Owing to methodological difficulties, available information on this subject is very limited.

One useful approach to examine the mechanics of human locomotive movements is to evaluate mechanical work done during the movements (Willems et al., 1995). Many studies calculated the work done and/or power generated during running by analyzing the ground reaction force (GRF) during the stance period (Cavagna, 1975; Cavagna et al., 1964, 1971, 1976; Cavagna and Kaneko, 1977; Fenn, 1930a,b; Fukunaga et al., 1980, 1981). In these studies, the work done at every step in running has been divided into two parts on the basis of the horizontal anterior–posterior GRF during the stance period: the work done during the braking phase (negative work) and propulsive phase (positive work), in which the runner's body decelerates and accelerates, respectively. However, only one provided extensive data on the changes in the work done at each step during the acceleration stage of maximal sprint running (Cavagna et al., 1971), although the presented data were limited to those in the horizontal anterior–posterior direction. From the previous findings, at about 7 m s^{-1}, the negative work done at each step, which immediately precedes the positive work, begins to increase, while the propelling force stops decreasing and becomes constant. On the basis of these findings, Cavagna et al. (1971) suggested that during low velocity running, the contractile component of the muscles is responsible for the power output, whereas during high velocity running, the mechanical energy is stored in the 'series elastic elements' during the negative work phase, and used to enhance power output in the positive work phase. This is indirectly supported by musculoskeletal modeling studies (Hof et al., 2002; Lai et al., 2014, 2016), indicating that the relative contribution of tendon elastic strain energy to the mechanical work done during sprint running expands with increasing running velocity.

In the report of Cavagna et al. (1971), however, it should be noted that the data on GRFs obtained during a single sprint were measured over only a few steps, because of the limitation in the length of force plates used (0.5 m×4). For constructing GRF data to recreate the entire acceleration stage of sprint running, the participants were required to perform several sprints on different days starting at various distances from the force plates. This approach calls into question the continuity of data acquisition and/or consistency of maximal effort by the runners. In addition, Cavagna et al. (1971) used only three sprinters as the participants and presented only individual data. In spite of these conditions, no studies have been conducted to corroborate the prior findings obtained over about half a century. The fastest intra-individual sprinting within a single session consisting of three to five maximal trials can be

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characterized by: (1) the exertion of a sufficient vertical impulse during the short support duration from the fourth step; (2) the large propulsive impulse and mean force during the initial acceleration; and (3) a large mean net anterior–posterior force during initial and middle acceleration (Nagahara et al., 2018c). These suggest that if one intends to elucidate the mechanics of maximal acceleration sprint running in relation to the performance, GRF data at every step should be measured continuously over the whole acceleration stage in the fastest intra-individual trial within a single session consisting of multi-sprints covering the entire distance examined.

Apart from the calculation of mechanical work, GRF data during accelerated sprint running over 10–50 m have been extensively analyzed to explain the inter-individual differences in running performance (Hunter et al., 2005; Kawamori et al., 2013; Morin et al., 2011, 2012, 2015; Nagahara et al., 2018a,b). Based on these findings, maintaining a high GRF during the propulsive phase and a low value during the braking phase in the horizontal anterior–posterior direction are essential to achieve a high running velocity. As a general rule, the execution of accelerated sprint running requires the runners to maximally accelerate their bodies in the forward direction. Considering these aspects, maximizing the work done during the propulsive phase in the horizontal anterior–posterior direction while suppressing any increase in the work done during the braking phase can be a strategy to achieve a high running velocity. However, this would partially contradict the idea described by Cavagna et al. (1971). Namely, if the relative contribution of the elastic strain energy stored during the braking phase to power output during the propulsive phase expands with increasing running velocity, work done during the braking phase might contribute to achieve high running performance (Hunter et al., 2005). Examining this will provide useful information concerning the energetics for achieving a high velocity in accelerated sprint running.

The present study aimed to elucidate the magnitude of the mechanical work done in each of the braking and propulsive phases during the acceleration stage of 60 m maximal sprint running and the associations of the work variables with running performance. To this end, we adopted a 50 m force plate system (Nagahara et al., 2018a,b,c) to continuously obtain GRFs at every step during the acceleration stage. We hypothesized that in maximal sprint running from a stationary start, while the work done during the propulsive phase in the horizontal anterior–posterior direction gradually decreases with increasing running velocity, it accounts for the majority of the total external work done during the acceleration stage and its difference from the work done during the braking phase can be a major factor affecting running performance.

MATERIALS AND METHODS

Participants

Twelve young males were recruited as the participants (age, 21.2±2.9 years; height, 1.736±0.062 m; mass, 69.8±11.4 kg; means±s.d.). Each of the subjects participated in sporting events involving sprint running (e.g. track and field, soccer or basketball). This study was approved by the Ethics Committee of the National Institute of Fitness and Sports in Kanoya and was consistent with the institutional ethical requirements for human experimentation in accordance with the Declaration of Helsinki. The participants were fully informed of the purpose and risks of the experiment and gave written informed consent.

Experimental setup

After warm-up, the participants were asked to perform maximal acceleration sprint running over 60 m 3–5 times on a 110 m indoor runway from a crouched position with starting blocks, wearing running shoes. The participants started to run on hearing a signal produced by an electronic starting gun connected to a computer linked to force plates, initiating the recording of GRF. A rest period of 5 min or more was set between the trials. At each step, GRFs in each of the horizontal medio–lateral, horizontal anterior–posterior and vertical axes was measured with a 50 m force plate system (Nagahara et al., 2018a,b,c), which consisted of 54 individual force plates (Tec Gihan Co. Ltd, Uji, Japan) consecutively placed from the starting area to 50 m mark. Among the force plates, four were set in the starting area: two for hands and two for feet. Each force plate for hands was 0.550 m wide, 0.300 m long and 0.085 m thick, and its mass was 23 kg and that for feet was 0.32 m wide, 1.20 m long, and 0.12 m thick, and its weight was 47 kg. The force plates set in the starting area were equipped with starting blocks. Each force plate set from the starting line to 50 m mark was 0.90 m wide, 1.00 m long, and 0.13 m thick, and its mass was 68 kg.

All force plates involved in the system were covered with the track surface (Resin Ace, Hasegawa Sports Facilities Co. Ltd, Tokyo, Japan) and designed to measure the force (**F**) applied to its top surface with strain gauges in the three axes of an orthogonal *x*-, *y*- and *z*-coordinate system: horizontal medio-lateral ($\mathbf{F}_x$), horizontal anterior–posterior ($\mathbf{F}_y$), and vertical ($\mathbf{F}_z$) axes (Fig. 1). The natural frequency of each of the force plates laid under the ground was determined by analyzing the damped oscillation of the force curve, induced by hitting the force plates with a hammer. The average value of the natural frequency for 54 force plates was 145 (±3.2) Hz for $\mathbf{F}_x$, 145 (±3.8) Hz for $\mathbf{F}_y$, and 217 (±7.0) Hz for $\mathbf{F}_z$. In the present study, therefore, the GRF data were digitized with 1 kHz and analyzed using a low-pass filter with a cut-off frequency of 100 Hz. The nonlinearity of the force plates was within ±1%. For the ground contact on the force plate, touchdown and toe-off were identified from the raw $\mathbf{F}_z$ data with a threshold of 30 N using a computer software program (MATLAB R2018a, MathWorks). The $\mathbf{F}_z$ data were also used to calculate the center of pressure (COP) position at each step in the horizontal anterior–posterior direction using a computer software program (Fig. 1D).

Data analysis

Calculation of running velocity

The duration of foot contact with the ground and that from toe-off of one leg to the next foot strike of the other leg were determined using MATLAB and defined as the support and aerial times, respectively. Similarly, the mean COP position 10 ms before and after the halfway point during foot contact was also calculated using MATLAB and defined as the location of foot contact. As a parameter representing sprint running performance, the time required to run 50 m ($T_{50\,\mathrm{m}}$) was calculated from changes in the position of COP. In the present study, the running velocity (V) at each step was obtained by differentiating the change in COP displacement between the two consecutive steps with respect to the time required. The peak value of V was referred to as the maximal running velocity (V_{max}). In addition to the absolute value, V at each step was expressed as the value relative to V_{max} (% V_{max}). The present study defined the running stage from block clearance to the point at which V_{max} appeared as the acceleration stage. With reference to a previous study (Nagahara et al., 2018c), the trial in which the highest V_{max} among the 3–5 sprints was observed was subjected to the following analysis.

Calculations of mechanical energy and work

In running, work done in the horizontal medio–lateral direction is much smaller than in the horizontal anterior–posterior and vertical directions, and so it can be neglected (Cavagna, 1975). Therefore,

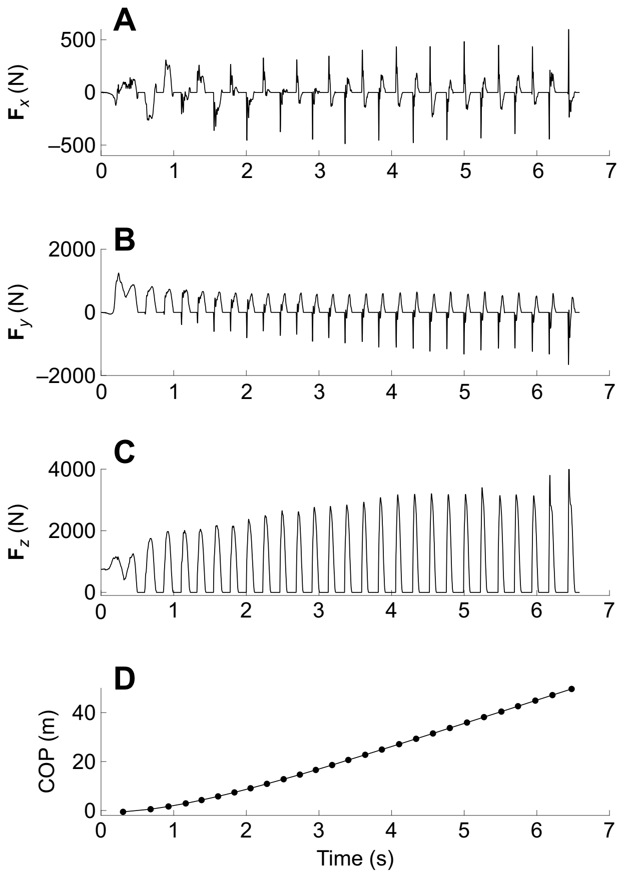

Fig. 1. Changes in GRFs and displacement in the position of the center of pressure during maximal sprint running. Horizontal medio–lateral GRF ($\mathbf{F}_x$, A), horizontal anterior–posterior GRF ($\mathbf{F}_y$, B), vertical GRF ($\mathbf{F}_z$, C) and the displacement in the center of pressure (COP) position (D) measured in the horizontal anterior–posterior direction for 27 steps over 50 m during 60 m maximal sprint running for one participant who was a sprinter. The COP position at each step was calculated using $\mathbf{F}_z$. The COP location when foot contact occurred across two adjacent force plates (force plates a and b) was determined using the following equation (Exell et al., 2011): $ay=ay_a\times(\mathbf{F}_{z,a}/\mathbf{F}_z)+ay_b\times(\mathbf{F}_{z,b}/\mathbf{F}_z)$ where ay is the global location of COP, ay_a and ay_b are COP locations measured by force plates a and b, respectively; $\mathbf{F}_{z,a}$ and $\mathbf{F}_{z,b}$ are vertical GRFs measured by force plates a and b, respectively, and $\mathbf{F}_z$ is the total vertical GRF measured by the two force plates.

the present study focused on the work done at each step in the horizontal anterior–posterior (W_{kap}) and vertical (W_v) directions and calculated it from the changes in kinetic energy in the horizontal anterior–posterior direction (E_{kap}) and potential and kinetic energy in the vertical direction (E_v), respectively (Cavagna et al., 1971; Cavagna, 1975). Briefly, E_{kap} at each step was calculated using the following equation:

$$E_{kap} = (M_b \times V_{ap}^2)/2, \tag{1}$$

where M_b is the body mass determined using a weighing device and V_{ap} is the velocity in the horizontal anterior–posterior direction, obtained by dividing the time integration of the first order for $\mathbf{F}_y$ by the body mass. E_v consists of the gravitational potential energy (E_p) and the kinetic energy due to the vertical component of the velocity (E_{kv}): $E_v=E_p+E_{kv}$ (Cavagna, 1975). E_p at every step was calculated using the following equation:

$$E_p = M_b \times \boldsymbol{g} \times dh, \tag{2}$$

where $\boldsymbol{g}$ is the gravitational acceleration and dh is the difference in height of the center of gravity of the body during the stance period from that at the starting position. Then, dh was calculated using the following equation:

$$dh = \iint (\mathbf{F}_z - k \times \mathrm{BW})/(k \times M_b)dt^2, \tag{3}$$

where BW is the body weight determined using a weighing device and k is the coefficient for BW and M_b in each participant. The weighing device-based body mass differed from the force plate-based body mass in each of the 54 force plates in the 50 m force plate system. The difference was very small. By conducting time integration of the second order for $\mathbf{F}_z$, however, the difference between the weighing device- and force plate-based body masses yielded a non-negligible error in the accumulated value of the vertical displacement of the center of gravity of the body mass from the start of the run to its finish over 50 m. Thus, we obtained k, which minimizes the standard deviation of dh at every step over 50 m using a trial-and-error iterative computation. The mean and s.d. of the k values for all participants were 0.99296±0.00754 (n=12). E_{kv} at every step was calculated using the following equation:

$$E_{kv} = (M_b \times V_v^2)/2, \tag{4}$$

where V_v is the vertical component of the velocity. Also, V_v at every step was calculated using the following equation:

$$V_v = \int (\mathbf{F}_z - k \times \mathrm{BW})dt/(k \times M_b). \tag{5}$$

The sum of E_{kap} and E_v at every step was defined as external mechanical energy (E_{ext}). External mechanical work (W_{ext}) at every step was calculated on the basis of the changes in E_{ext}.

In each of E_{kap} (Fig. 2A), E_v (Fig. 2B) and E_{ext} (Fig. 2C), the periods between landing and the point at which the energy value became minimal and between the point at which the minimum value appeared and toe-off were defined as the braking and propulsive phases, respectively. The W_{kap}, W_v and W_{ext} values in the braking phase were referred to as $-W_{kap}$, $-W_v$ and $-W_{ext}$, respectively, and those in the propulsive phase as $+W_{kap}$, $+W_v$ and $+W_{ext}$, respectively. In addition, the differences between $|-W_{kap}|$ and $+W_{kap}$ (ΔW_{kap}), between $|-W_v|$ and $+W_v$ (ΔW_v), and between $|-W_{ext}|$ and $+W_{ext}$ (ΔW_{ext}) were calculated. Each work parameter was expressed as the value relative to body mass. The total values of each work parameter at every step over 50 m and in each of 0–10, 10–20, 20–30, 30–40 and 40–50 m sections were calculated to examine their associations with $T_{50\,m}$. In addition, the mean values of mechanical power ($P_{kap,\,mech}$) and force ($\mathbf{F}_{y,\,mech}$) in each of braking ($-P_{kap,\,mech}$ and $-\mathbf{F}_{y,\,mech}$, respectively) and propulsive ($+P_{kap,\,ech}$ and $+\mathbf{F}_{y,\,mech}$, respectively) phases at every step in the horizontal anterior–posterior direction were calculated by dividing the relevant work and impulse parameters by the corresponding time to examine the associations between the power and force variables. Each of power and force variables was expressed as the value relative to body mass.

Statistics

Descriptive data are presented as means±s.d. In this study, $\%V_{max}$ had already reached around 20% at block clearance (Fig. 3). Thus, the means and s.d. for the analyzed variables are presented at intervals of 10% V_{max} in a range of 20% V_{max} or higher. The value at every 10% V_{max} for each participant was obtained by applying a

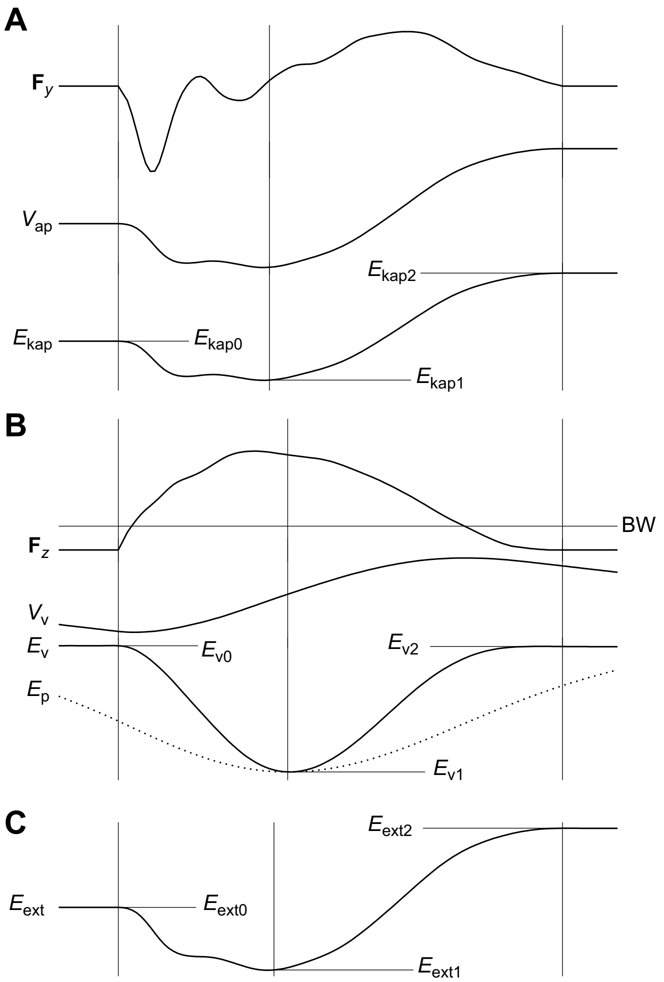

Fig. 2. Calculations of mechanical work. In each of E_{kap} (A), E_v (B) and E_{ext} (C), the periods between landing and the point at which the energy value becomes minimal and between the point at which the minimum value appears and toe-off were defined as braking and propulsive phases, respectively. The W_{kap}, W_v and W_{ext} values in the braking phase are referred to as $-W_{kap}$, $-W_v$ and $-W_{ext}$, respectively, and those in the propulsive phase $+W_{kap}$, $+W_v$ and $+W_{ext}$, respectively. $-W_{kap}$ at each step was obtained as the difference between E_{kap} at landing (E_{kap0}) and the minimum E_{kap} (E_{kap1}) and $+W_{kap}$ at each step as the difference between the minimum E_{kap} (E_{kap1}) and E_{kap} at toe-off (E_{kap2}). $-W_v$ at each step was obtained as the difference between E_v at landing (E_{v0}) and the minimum E_v (E_{v1}) and $+W_v$ as the difference between the minimum E_v (E_{v1}) and E_v at toe-off (E_{v2}). $-W_{ext}$ at each step was obtained as the difference between E_{ext} at landing (E_{ext0}) and the minimum E_{ext} (E_{ext1}) and $+W_{ext}$ at each step as the difference between minimum E_{ext} (E_{ext1}) and E_{ext} at toe-off (E_{ext2}).

cubic method to two known data points adjacent to the corresponding $\%V_{max}$. In this process, two participants exceeded 20% V_{max} at block clearance, and so the mean and s.d. for each variable at 20% V_{max} were calculated using data for the remainder (n=10). Pearson product–moment correlation coefficients (r) were calculated to determine the relationships between $+P_{kap,\,mean}$ and each of $|-P_{kap,\,mean}|$, $+\mathbf{F}_{y,\,mean}$ and $|-\mathbf{F}_{y,\,mean}|$ and between each of the work variables and $T_{50\ m}$. The significance level was set at $P<0.05$. All statistical analyses were performed using MATLAB.

RESULTS

$T_{50\ m}$ and V_{max} were 7.11±0.54 s and 8.67±0.75 m s^{-1}, respectively. The total number of steps over 50 m, including block clearance, was 30.3±1.8. Velocity sharply increased from block clearance and reached 50% V_{max} within 1 s, and then increased in a hyperbolic convex upward manner until about 3–4 s (Fig. 3). V_{max} was reached at 36.87±7.76 m (5.49±0.65 s) from the starting line. In terms of the average value, the runners reached 90% V_{max} at a running distance corresponding to 35.4% of that required to attain 100% V_{max} (Table 1), indicating that the runners had already achieved a running velocity close to V_{max} in the earlier period of the acceleration stage.

In terms of the average value, $+W_{kap}$ at every 10% V_{max} was more than 3.6 J kg^{-1} with relatively small changes until 70% V_{max}, and then it decreased to 2.4 J kg^{-1} at 100% V_{max} (Fig. 4A). $|-W_{kap}|$ was less than 0.3 J kg^{-1} at 70% V_{max} or lower, but it nonlinearly increased at 80% V_{max} or higher and reached 1.9 J kg^{-1} at 100% V_{max}. $+W_v$ decreased from 1.7 J kg^{-1} at 20% V_{max} to 0.6 J kg^{-1} at

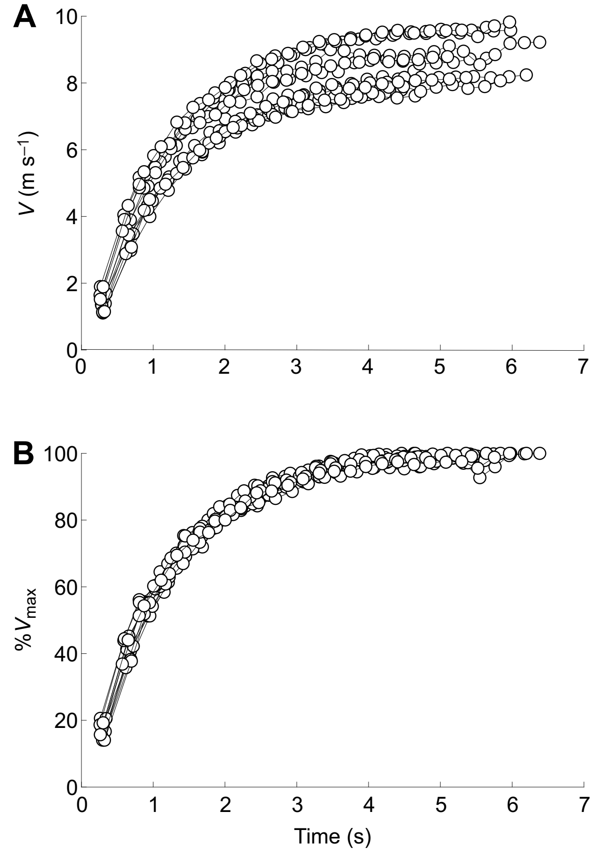

Fig. 3. Changes in V and $\%V_{max}$ from block clearance to the time at which V_{max} was reached. The presented data are individual data for V (A) and $\%V_{max}$ (B) of all participants (n=12).

Table 1. Running velocity (V), running time (T), running distance from the starting line (D) and number of steps at increasing $\%V_{max}$

$\%V_{max}$	n	V (m s^{-1})	T (s)	D (m)	No. steps
20	10	1.73±0.16	0.35±0.04	−0.43±0.06	1.2±0.1
30	12	2.60±0.23	0.49±0.05	−0.10±0.12	1.6±0.1
40	12	3.47±0.30	0.64±0.06	0.29±0.16	2.0±0.2
50	12	4.34±0.38	0.82±0.08	1.03±0.24	2.7±0.2
60	12	5.20±0.45	1.09±0.07	2.31±0.33	3.8±0.2
70	12	6.07±0.53	1.42±0.09	4.18±0.57	5.3±0.4
80	12	6.94±0.60	1.89±0.09	7.31±1.02	7.5±0.5
90	12	7.80±0.68	2.67±0.19	13.04±1.85	10.9±1.0
100	12	8.67±0.75	5.49±0.65	36.87±7.76	23.6±3.5

All values are means±s.d.

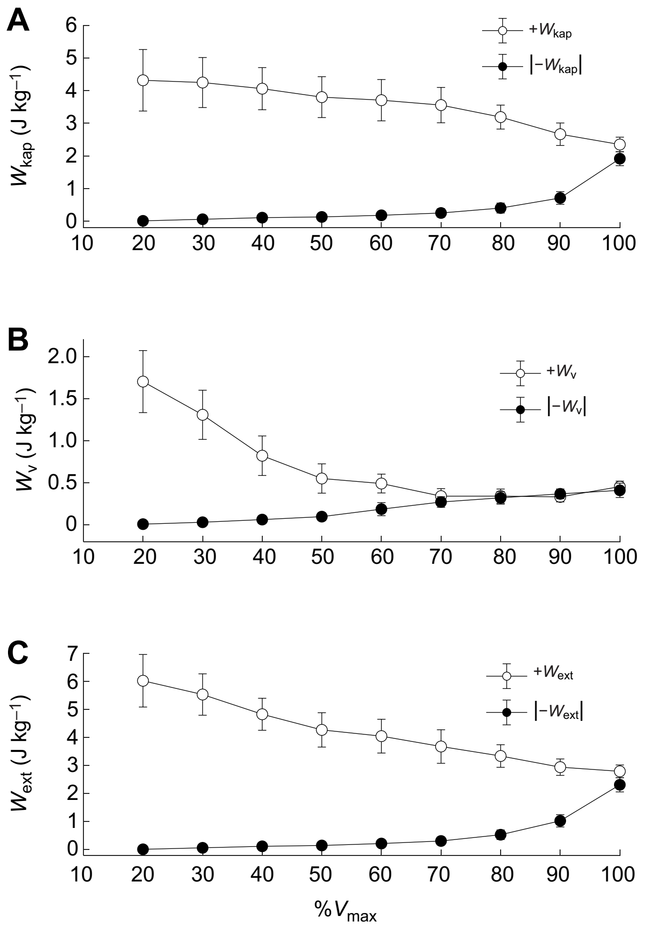

Fig. 4. Changes in work parameters over increasing %V_{max} values. W_{kap} (A), W_v (B) and W_{ext} (C) at every 10% V_{max} from 20 to 100% V_{max}. The presented data are means±s.d. The means and s.d. at 20% V_{max} were calculated using data for 10 participants, and those at 30% V_{max} and above were calculated using data for 12 participants.

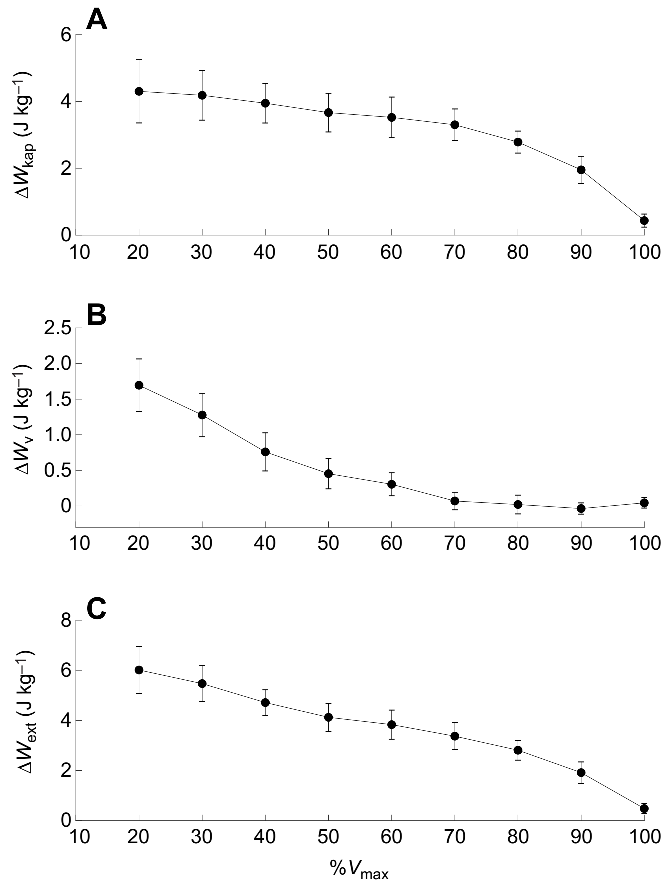

Fig. 5. Changes in the difference between positive and negative phases of work parameters over increasing %V_{max} values. ΔW_{kap} (A), ΔW_v (B) and ΔW_{ext} (C) at every 10% V_{max} from 20 to 100% V_{max}. The presented data are means±s.d. The means and s.d. at 20% V_{max} were calculated using data for 10 participants, and those at 30% V_{max} and above were calculated using data for 12 participants.

50% V_{max}, and |−W_v| was less than 0.4 J kg^{-1} even at 100% V_{max} (Fig. 4B). +W_{ext} linearly decreased from 6.0 J kg^{-1} at 20% V_{max} to 2.8 J kg^{-1} at 100% V_{max}, and |−W_{ext}| was less than 0.5 J kg^{-1} until 80% V_{max}, and then it abruptly increased to 2.3 J kg^{-1} at 100% V_{max} (Fig. 4C).

At 70% V_{max} or lower, while the change in $ΔW_{kap}$ was small (Fig. 5A), $ΔW_v$ abruptly decreased (Fig. 5B). At 70% V_{max} or higher, $ΔW_{kap}$ sharply decreased, but $ΔW_v$ was mostly constant. $ΔW_{ext}$ linearly decreased with increasing running velocity (Fig. 5C).

On comparing the average values of the total of each work parameter at every step over 50 m, +W_{kap} was greater than |−W_{kap}|, +W_v, and |−W_v| by 2.3, 5.8 and 7.9 times, respectively (Table 2). Reflecting the difference between +W_{kap} and |−W_{kap}|, the total of +W_{ext} at every step was 2.1 times greater than that for |−W_{ext}|.

+$\mathbf{F}_{y,\,mech}$ linearly decreased until 80% V_{max} and then it became mostly constant (Fig. 6A). |−$\mathbf{F}_{y,\,mean}$| gradually increased with increasing running velocity. +$P_{kap,\,mean}$ and |−$P_{kap,\,mean}$| increased with increasing running velocity until 100% V_{max} (Fig. 6B). Differences between +$\mathbf{F}_{y,\,mean}$ and |−$\mathbf{F}_{y,\,mean}$| and between +$P_{kap,\,mean}$ and |−$P_{kap,\,mean}$| became negligible at 100% V_{max}.

+$P_{kap,\,mean}$ was more strongly correlated with +$\mathbf{F}_{y,\,mech}$ at every 10% V_{max} in a range from 20 to 100% V_{max} (Table 3). On the other hand, there were no significant correlations between +$P_{kap,\,mean}$ and either |−$\mathbf{F}_{y,\,mean}$| or |−$P_{kap,\,mean}$| and between +$\mathbf{F}_{y,\,mean}$ and |−$\mathbf{F}_{y,\,mean}$| at every 10% V_{max}, with the exception that the association between +$P_{kap,\,mean}$ and |−$\mathbf{F}_{y,\,mean}$| at 100% V_{max} was significant.

The total value of $ΔW_{kap}$ over 50 m was more strongly correlated with $T_{50\ m}$ as compared with those of the other work variables (Table 4). In terms of the total work over each 10 m section, too, the $ΔW_{kap}$ values in all distance sections except for the 40–50 m section were highly correlated with $T_{50\ m}$, notably in the first two distance sections.

DISCUSSION

The findings obtained here indicated that in maximal sprint running over 50 m, +W_{kap} accounted for the majority of the total external

Table 2. Total work done over 50 m (*n*=12)

Variable	Mean±s.d.
+W_{kap}	82.4±7.5 J kg^{-1}
|−W_{kap}|	36.2±4.4 J kg^{-1}
$ΔW_{kap}$	46.4±9.3 J kg^{-1}
+W_v	14.3±1.9 J kg^{-1}
|−W_v|	10.4±1.2 J kg^{-1}
$ΔW_v$	4.0±1.3 J kg^{-1}
+W_{ext}	95.2±6.2 J kg^{-1}
|−W_{ext}|	45.0±4.9 J kg^{-1}
$ΔW_{ext}$	50.2±9.3 J kg^{-1}

Values are means±s.d.

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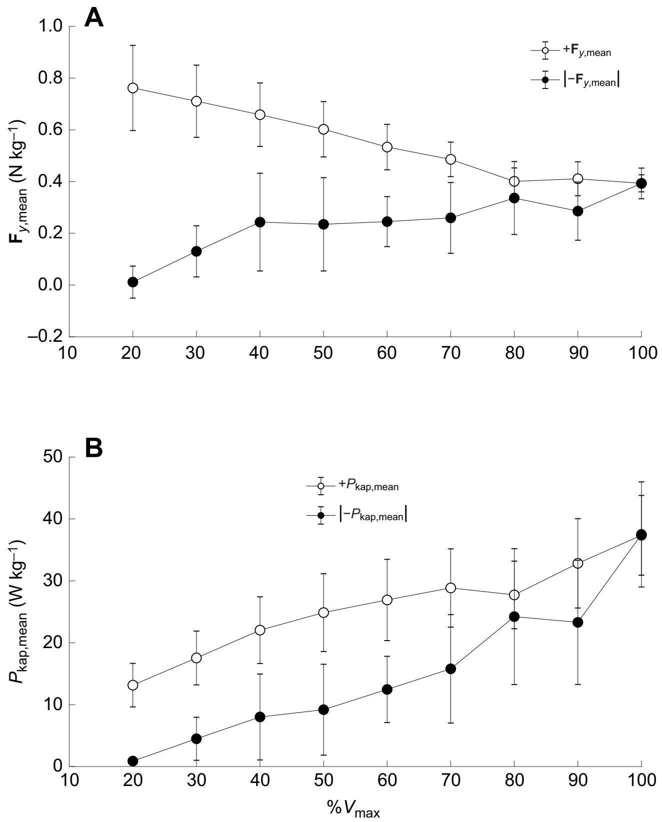

Fig. 6. Changes in force and mechanical power over increasing %V_{max} values. $\mathbf{F}_{y,\ mean}$ (A) and $P_{kap,\ mean}$ (B) at every 10% V_{max} from 20 to 100% V_{max}. The presented data are means±s.d. The means and s.d. at 20% V_{max} were calculated using data for 10 participants, and those at 30% V_{max} and above were calculated using data for 12 participants.

work done during the acceleration stage, and the total value of ΔW_{kap} at every step over 50 m was closely correlated with $T_{50\ m}$. These results support our hypothesis set at the start of this study.

$+W_v$ was relatively large at 20% V_{max}. For most of the participants, 20% V_{max} corresponded to the running velocity just after the completion of block clearance (Fig. 3). Thus, the greater $+W_p$ at 20% V_{max} may be a result reflecting the work requirement during block clearance in which the runners need to raise their bodies from a crouched position through block clearance, accompanying a propulsive action in the forward direction. Regardless of %V_{max}, however, the parameters of W_v were markedly smaller than $+W_{kap}$ (Fig. 4). This suggests that the runners sprinted over 50 m while doing more work in the propulsive phase of the horizontal posterior–anterior direction, and minimizing work done in the vertical direction.

Table 3. Correlation coefficients between mechanical power and force at every 10% V_{max} from 20 to 100% V_{max}

%V_{max}	n	$+P_{kap,\ mean}$ vs $\lvert -P_{kap,\ mean}\rvert$	$+P_{kap,\ mean}$ vs $+\mathbf{F}_{y,\ mean}$	$+P_{kap,\ mean}$ vs $\lvert -\mathbf{F}_{y,\ mean}\rvert$	$+\mathbf{F}_{y,\ mean}$ vs $\lvert -\mathbf{F}_{y,\ mean}\rvert$
20	10	−0.160	0.970****	−0.382	−0.145
30	12	0.099	0.959****	0.228	0.209
40	12	0.196	0.956****	0.297	0.301
50	12	0.125	0.964****	0.205	0.143
60	12	0.338	0.971****	0.541	0.341
70	12	0.406	0.957****	0.548	0.504
80	12	0.330	0.913****	0.502	0.275
90	12	−0.139	0.918****	0.050	−0.338
100	12	0.406	0.829***	0.717**	0.366

**P<0.01; ***P<0.001; ****P<0.0001.

Reflecting the changes in $+W_{kap}$ and $|-W_{kap}|$ until 70% V_{max} from the start of the run (Fig. 4), the reduction in ΔW_{kap} in the velocity range was relatively small (Fig. 5). Considering that the runners reached 70% V_{max} at 4.1 m from block clearance (Table 1), the current results indicate that in the early period of the acceleration stage, the runners propelled their bodies in the forward direction with less deceleration. This will be partially associated with the changes in the runner's posture and/or motion during the acceleration stage. Greater accelerations can be generated by more forward-oriented forces, and the orientation of the *GRF* vector is closely associated with the forward lean of the body at toe-off (Kugler and Janshen, 2010). In addition, it has been shown that in accelerated sprint running, the foot position on ground touchdown changes from behind to in front of the center of gravity of the body after the fourth step (Nagahara et al., 2014). The horizontal anterior–posterior distance between the center of gravity of the body and metatarsophalangeal joints of the support leg becomes a primary reason for the decrease in running velocity during the stance period (Mero et al., 1992), and a smaller distance suppresses the magnitude of the horizontal ground reaction impulse during the braking phase (Hunter et al., 2005). In the current results, the runners reached 60–70% V_{max} at the 4th–5th steps (Table 1). Thus, the changes in $+W_{kap}$ and $-W_{kap}$ at around 70–80% V_{max} may be partially attributable to the magnitude of forward lean of the body at toe-off and/or the foot position on ground touchdown during the initial phase of the acceleration stage.

$-W_{kap}$ increased at 80% V_{max} or higher and its difference from $+W_{kap}$ became small at 100% V_{max}. Cavagna et al. (1971) reported that the negative work done at each step began to increase when the running velocity reached about 7 m s^{-1}. In the current study, the average running velocity corresponding to 80% V_{max}, at which $-W_{kap}$ started to increase, was 6.94 m s^{-1} (Table 1). This agrees with the results of Cavagna et al. (1971), in spite of the difference in the procedure for measuring GRFs between the present (single-sprint) and previous (multi-sprint) studies. At the start of this study, we questioned the validity of GRF data obtained by multi-sprints in terms of the continuity of data acquisition and/or the consistency of maximal effort by the participants. With respect to the running velocity at which the negative work done in the horizontal anterior–posterior direction starts to increase, the current results support the previous findings (Cavagna et al., 1971). The present study analyzed the fastest intra-individual sprint among three to five 60 m sprints with reference to the report of Nagahara et al. (2018c). In their results, however, it is also true that there was no clear difference between the fastest and slowest intra-individual trials in the changes of step-to-step spatiotemporal variables and GRFs across the step number. Thus, the difference between the procedures to obtain GRF data (single sprint vs multi-sprints) might have produced a difference in the magnitude of the work values, but not induced that in the pattern of changes of the work values across running velocities.

It has been considered that the power output during the early stage of accelerated sprint running is mainly derived from the contractile components of the muscles, and the augmentation of the negative work at a high running velocity increases the mechanical energy stored in the elastic elements and enhances its contribution to power output during running (Cavagna et al., 1971). As evidence to support this, it has been shown that concentric force and power development

Table 4. Correlation coefficients of the total work done in each of five distance sections and over 50 m with $T_{50\ m}$ (n=12)

	Distance section					
Variables (J kg^{-1})	0–10 m	10–20 m	20–30 m	30–40 m	40–50 m	0–50 m
$+W_{kap}$	−0.920****	−0.871***	−0.612*	−0.613*	−0.457	−0.894****
$\lvert -W_{kap}\rvert$	0.010	0.619*	0.533	0.585*	0.203	0.496
ΔW_{kap}	−0.920****	−0.911****	−0.806**	−0.811**	−0.349	−0.946****
$+W_v$	0.261	0.464	0.655*	0.833***	0.581*	0.670*
$\lvert -W_v\rvert$	0.561	0.636*	0.749**	0.620*	0.651*	0.822**
ΔW_v	−0.157	−0.270	0.063	0.096	0.061	0.189
$+W_{ext}$	−0.884***	−0.819**	−0.535	−0.483	−0.170	−0.850***
$\lvert -W_{ext}\rvert$	0.293	0.722**	0.638*	0.776**	0.339	0.668*
ΔW_{ext}	−0.871***	−0.877***	−0.801**	−0.860***	−0.366	−0.929****

*P<0.05; **P<0.01; ***P<0.001; ****P<0.0001.

are critical to sprint performance over a very short distance (less than 10 m) (Chelly and Denis, 2001; Sleivert and Taingahue, 2004; Young et al., 1995). In addition, musculoskeletal modeling studies (Hof et al., 2002; Lai et al., 2014, 2016) have shown that the relative contribution of tendon elastic strain energy to the mechanical work during sprint running increases with increasing running velocity, although these focused on the behavior of a given muscle-tendon unit. Considering these findings, at 80% V_{max} or higher, in which $+W_{kap}$ decreased and $-W_{kap}$ largely increased with increasing running velocity, either $\lvert -\mathbf{F}_{y,\,mean}\rvert$ or $\lvert -P_{kap,\,mean}\rvert$ might be positively associated with $+P_{kap,\,mean}$. Certainly, the current result that at 80% V_{max} or higher, $+P_{kap,\,mean}$ still increased while $+\mathbf{F}_{y,\,mean}$ became mostly constant suggests the contribution of tendon elastic energy to power generation at a high velocity running (Cavagna et al., 1971). At increments of 10% V_{max} ranging from 20 to 100% V_{max}, however, only the $\lvert -\mathbf{F}_{y,\,mean}\rvert$ at 100% V_{max} was significantly correlated with $+P_{kap,\,mean}$. By contrast, $P_{kap,\,mean}$ was closely related to $+\mathbf{F}_{y,\,mean}$ at every 10% V_{max} over the entire acceleration stage until 100% V_{max}. These results indicate that until 90% V_{max} from block clearance, i.e. in most of the acceleration stage, muscle work done during the propulsive phase mainly contributes to generate $+P_{kap,\,mean}$, and the contribution of tendon elastic energy stored in the braking phase (Cavagna et al., 1971), if present, could be realized at around 100% V_{max}.

The total of each of ΔW_{kap} at every step over 50 m was strongly correlated with $T_{50\ m}$. This agrees with previous reports indicating that maintaining a high GRF during the propulsive phase and a low value during the braking phase in the horizontal anterior–posterior direction are major determinants for achieving a high running velocity (Kawamori et al., 2013; Hunter et al., 2005; Morin et al., 2015; Nagahara et al., 2018a). In terms of the total work done in each 10 m section, ΔW_{kap} was highly correlated with $T_{50\ m}$ in all distance sections except for 40–50 m, notably in the 0–20 m section (Table 4). Thus, it can be said that at least on maximal sprint running over 50 m, maximizing $+W_{kap}$ while suppressing an increase in $\lvert -W_{kap}\rvert$, notably in the early stage (less than 20 m) of the running distance, is one of the major determinants for achieving better total running performance. At the same time, the observed association between ΔW_{kap} and $T_{50\ m}$ rules out the possibility that the tendon elastic energy stored during the braking phase in the horizontal anterior–posterior direction (Cavagna et al., 1971) might contribute to better performance in accelerated sprint running over 50 m.

In addition to the horizontal anterior–posterior GRFs, many studies have already examined the influences of the vertical GRF during sprint running on running performance (Hunter et al., 2005; Kawamori et al., 2013; Morin et al., 2011, 2012, 2015; Nagahara et al., 2018a,b; Weyand et al., 2000). Among these studies, only one attempted to separately analyze the vertical GRF for each of braking and propulsive phases and to examine their associations with sprint performance (Nagahara et al., 2018b). From the limited findings, no significant correlations were found between sprint performance and vertical ground reaction impulses of either braking or propulsive phases (Nagahara et al., 2018b). In the current results, the total $+W_v$ and $\lvert -W_v\rvert$ over 50 m and specific running distances were positively correlated with $T_{50\ m}$. This indicates that, in a similar way to the work done during the braking phase in the horizontal anterior–posterior direction, how the runner can minimize the work done during the braking and propulsive phases in the vertical direction will also be a factor leading to a high running performance over 50 m.

The present study had some limitations. It involved only young adult males as the participants, and notably did not involve elite sprinters. Further investigation including these subjects is required to elucidate the mechanics of maximal acceleration sprint running in elite athletes specifically trained to maximize the acceleration ability and determine factors for better sprint running performance. In addition, the present study did not conduct measurements concerning body kinematics and orientation during maximal sprint running. In the future, studies involving measurements of both kinetics and kinematics during sprint running will be needed to elucidate the association between body kinematics and work variables during sprint running.

In summary, the present study indicates that in maximal sprint running over 50 m, work done during the propulsive phase in the horizontal anterior–posterior direction accounts for the majority of the total external work done during the acceleration stage, and maximizing it while suppressing work done during the braking phase is essential to achieve a high running performance.

Competing interests
The authors declare no competing or financial interests.

Author contributions
Conceptualization: T.F., H.K.; Methodology: A.M., M.M., R.N., T.F., H.K.; Software: A.M.; Formal analysis: A.M., M.M., R.N.; Investigation: A.M., M.M., R.N., T.F., H.K.; Data curation: A.M., M.M., R.N., T.F., H.K.; Writing - original draft: A.M., M.M., R.N., T.F., H.K.; Writing - review & editing: A.M., M.M., R.N., T.F., H.K.; Supervision: T.F., H.K.; Project administration: A.M., T.F., H.K.

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Data availability
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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