Analysis of lower limb work-energy patterns in world-class race walkers

Brian Hanley and Athanassios Bissas

School of Sport, Carnegie Faculty, Headingley Campus, Leeds Beckett University, United Kingdom

Correspondence details:

Brian Hanley,

Fairfax Hall,

Headingley Campus,

Leeds Beckett University,

LS6 3QS,

United Kingdom.

Telephone: +44 113 812 3577

Fax: +44 113 283 3170

Email: b.hanley@leedsbeckett.ac.uk

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ABSTRACT

The aim of this study was to analyse lower limb work patterns in world-class race walkers. Seventeen male and female athletes race walked at competitive pace. Ground reaction forces (1000 Hz) and high-speed videos (100 Hz) were recorded and normalised joint moments, work and power, stride length, stride frequency and speed estimated. The hip flexors and extensors were the main generators of energy (24.5 J (± 6.9) and 40.3 J (± 8.3) respectively), with the ankle plantarflexors (16.3 J (± 4.3)) contributing to the energy generated during late stance. The knee generated little energy but performed considerable negative work during swing (–49.1 J (± 8.7)); the energy absorbed by the knee extensors was associated with smaller changes in velocity during stance (r = .783, P < .001), as was the energy generated by the hip flexors (r = –.689, P = .002). The knee flexors did most negative work (–38.6 J (± 5.8)) and the frequent injuries to the hamstrings are probably due to this considerable negative work. Coaches should note the important contributions of the hip and ankle muscles to energy generation and the need to develop knee flexor strength in reducing the risk of injury.

INTRODUCTION

Race walking is an Olympic event dictated by a rule that no visible (to the human eye) loss of contact with the ground should occur and that the leg must be straightened from first contact with the ground until the 'vertical upright position' (Rule 230.2) (IAAF, 2015). Competitions are held over 20 km and 50 km and are therefore endurance events similar to the marathon. A comprehensive understanding of the role of major muscle groups in elite-standard race walking is clearly important to develop appropriate training methods that consider the specific demands of this unique form of competitive gait. The role of mechanical work in race walking was described in earlier work (Cavagna & Franzetti, 1981; Marchetti, Cappozzo, Figura, & Felici, 1982) but might not apply to current race walkers given those studies were conducted under the pre-1995 rule which did not require a straightened knee at first contact. In addition, whereas muscle moment values for the lower limb joints have been measured for modern race walkers (Hanley & Bissas, 2013; Hoga, Ae, Enomoto, Yokozawa, & Fujii, 2006), the crucial role of mechanical work has not been similarly reported.

The combination of kinetic, kinematic and anthropometric data allows for the calculation of joint moments, powers and work through processes of inverse dynamics (Winter, 1979). Despite its value in a detailed understanding of movement function, work has rarely been reported for competitive gait, including elite-standard sprinting (Bezodis, Kerwin, & Salo, 2008). Muscles acting concentrically do positive work whereas those acting eccentrically do negative work (Vardaxis & Hoshizaki, 1989); negative work by muscles is important as elastic energy is stored that can be converted to kinetic energy with resulting power generation (Cavagna, Dusman, &

Margaria, 1968) via the stretch-shortening cycle mechanism that increases efficiency (Cavagna, Saibene, & Margaria, 1964). Research has shown that race walking is more efficient than normal walking (Cavagna & Franzetti, 1981; Pavei, Cazzola, La Torre, & Minetti, 2014) probably because of elastic energy return, but less efficient and with a higher energy cost than running (Marchetti et al., 1982). However, the eccentric actions that allow for power absorption also have the potential to lead to injury because of the large stress experienced by muscles under strain (LaStayo et al., 2003); the measurement of positive and negative work phases in elite-standard race walking will help explain the association with better performances and common injuries. Previous research has analysed the lower limb joint moment and power patterns in race walkers (e.g. Hanley & Bissas, 2013; Hoga, Ae, Enomoto, & Fujii, 2003; Hoga et al., 2006) but whereas those studies reported peak moment and power magnitudes, more useful findings can be obtained from analysing mechanical work throughout specific gait phases. Better competition times in race walking arise from smaller deceleration phases during braking in early stance and subsequent smaller acceleration phases during late stance (Hanley & Bissas, 2016), and it would therefore be valuable to analyse the work done during these and other phases of the gait cycle to see which muscle groups are important in achieving this.

Despite the high profile of race walking, no research has measured the work done at the major lower limb joints and its relationship with key spatiotemporal variables. A thorough description and understanding of the muscular work performed in world-class race walkers will allow coaches and athletes to develop training regimens that emphasise correct technique and appropriate strength development, while considering areas potentially at risk of injury. The aim of this study was to analyse lower limb work magnitudes and patterns in world-class male and female race walkers. It was hypothesised that the requirement for race walkers to maintain a straightened knee from initial contact to midstance would diminish work generation by the knee, and increase that of the hip and ankle.

METHODS

Participants

The study was approved by the Faculty Research Ethics Committee and 17 race walkers of 10 different nationalities gave written informed consent. The athletes comprised 10 men (26 ± 3 yrs, 1.79 ± .05 m, 67.1 ± 7.9 kg) and seven women (26 ± 5 yrs, 1.66 ± .05 m, 55.8 ± 4.8 kg). All athletes had competed at the Olympic Games or World Championships in the two years before testing, which was performed during the race walking competitive season (i.e. between May and August). All 10 men had competed over 20 km (personal best time: 1:23:29 ± 1:59) with eight also competing over 50 km (3:51:34 ± 4:38). The mean personal best time for the seven women over their competitive distance of 20 km was 1:30:55 (± 1:47).

Data collection

Each athlete race walked along a 45 m indoor track at a speed equivalent to their season's best time (20 km or 50 km for men dependent on specialism). Timing gates were placed 4 m apart around two force plates (Kistler, Winterthur) that recorded both left and right foot contact phases and flight time. Athletes completed at least 10 trials (approximately 30% of trials were removed because athletes did not contact both force plates) and the three closest to the target time were analysed (within 3% of the target time). The force plates (1000 Hz) were placed in a customised housing in the centre of the track, and were covered with a synthetic athletic surface so that the force plate area was flush with the runway to preserve ecological validity (Bezodis et al., 2008).

To analyse the sagittal plane movements of the hip, knee and ankle, video data were collected at 100 Hz using a high-speed camera (Fastec, San Diego, CA). The shutter speed was 1/500 s, the *f*-stop was 2.0, and there was no gain. The camera was placed approximately 12 m from and perpendicular to the line of walking. The resolution of the camera was 1280 x 1024 pixels. Extra illumination was provided by 26 lights providing 4 kW each of overhead floodlighting. The force plate software and the camera system were synchronised using a Kistler connection box (Kistler, Winterthur).

Data analysis

The video files were manually digitised by a single experienced operator to obtain kinematic data (SIMI Motion, Munich). Digitising was started at least 10 frames before the beginning of the stride and completed at least 10 frames after to provide padding during filtering (Smith, 1989). Each video was first digitised frame by frame and adjustments made as necessary using the points over frame method (Bahamonde & Stevens, 2006). Dropout occurred on the left hand side of the body on some occasions and estimations were made by the operator. De Leva's (1996) fourteen-segment body segment parameter (BSP) model was used to obtain data for the whole body centre of mass (CM), right thigh, right lower leg, and right foot. The segment endpoints used for the lower limb segments were the hip joint, knee joint, ankle joint and tip of the second toe. Two separate approaches were taken for removing noise

(Giakas & Baltzopoulos, 1997): a cross-validated quintic spline smoothed the raw data before coordinate calculations (e.g. CM horizontal position), whereas a recursive second-order, low-pass Butterworth digital filter (zero phase-lag) filtered the same raw data and then first and second derivatives were obtained. The cut-off frequencies were calculated using residual analysis (Winter, 1979) and ranged between 7.6 and 11.5 Hz.

The ground reaction force (GRF) and centre of pressure data were analysed using Bioware version 3.20 (Kistler, Winterthur). The GRF data were first smoothed using a recursive second-order, low-pass Butterworth filter (zero phase-lag). The optimal cut-off frequency was calculated during a pilot test (three trials) using residual analysis (Winter, 1979). The results showed an optimal cut-off frequency ranging from 47 – 52 Hz in all three force directions, so 50 Hz was chosen as the cut-off frequency. However, because errors have been found to occur during initial contact in similar movements such as sprinting (Bezodis, Salo, & Trewartha, 2014), the first 60 ms of the GRF data were filtered at 10 Hz to match the low cut-off frequencies of the kinematic data and therefore minimise inaccuracies during impact (Bisseling & Hof, 2006).

Race walking speed was determined as the mean horizontal speed of the CM during one complete gait cycle. Stride length was measured as the horizontal distance between successive right foot contacts; it was also expressed as a percentage of the participants' statures, and referred to as stride length ratio. Stride frequency was calculated by dividing horizontal speed by stride length (Mero & Komi, 1994). The distance the CM travelled during flight was measured from the instant of toe-off on one foot to the instant of initial contact on the other foot and termed ‘flight distance’ (Hunter, Marshall, & McNair, 2004). ‘Foot ahead’ was used to describe the horizontal distance from the right foot to the CM at initial contact. Similarly, ‘foot behind’ was the horizontal distance from the right foot to the CM at toe-off. Both of these distances were also expressed as a proportion of stature and referred to as foot ahead ratio and foot behind ratio respectively. The hip angle was defined as the sagittal plane angle between the trunk and thigh segments. The knee angle was calculated as the sagittal plane angle between the thigh and leg segments. Both hip and knee angles were considered to be 180° in the anatomical standing position and angles beyond this as hyperextension. The ankle angle was calculated using the lower leg and foot segments and considered to be 110° in the anatomical standing position (Cairns, Burdette, Pisciotta, & Simon, 1986). The change in horizontal velocity of the CM was calculated using impulse measurements from the force traces in two sections during stance: when the foot was ahead of the CM from initial contact to midstance (decrease in velocity), and when the foot was behind the CM from midstance to toe-off (increase in velocity). Net change in velocity was calculated from net impulse over the whole contact phase, and the positive and negative impulses were summed to calculate gross change in velocity (Hanley & Bissas, 2016).

The filtered GRF data were matched with the kinematic data (Bezodis et al., 2008) and extracted at 100 Hz. These data were used to calculate net joint moments using a link segment rigid body model (Winter, 1979). Power was calculated by multiplying the moment by the joint angular velocity; positive power indicated that mechanical energy was being generated, whereas negative power indicated energy absorption

(White & Winter, 1985). The amount of work done at each joint was calculated as the time integral of the power curve using the trapezoidal rule (Bezodis et al., 2014). The total amount of work performed at each joint during specific phases was calculated to show the contribution of different muscle groups. To identify key events during the gait cycle, specific peaks on each power trace are labelled A1, K2, etc. in a similar fashion to previous studies (Bezodis et al., 2008; Hanley & Bissas, 2013).

Statistical analysis

Pearson's product moment correlation coefficient found associations between normalised work and key variables in race walking; an alpha level of 5% was set. To help reduce the chances of a type I error, only those correlations greater than 0.5, and therefore large effect sizes (Cohen, 1988), were included in this study.

RESULTS

The traces of the averaged joint normalised powers of the ankle, knee and hip are shown in Figure 1. The larger dashed vertical line represents heel strike, so that the first part of each trace shows swing, and the second shows stance (DeVita, 1994), whereas the smaller dashed vertical lines show when the net moments were flexor or extensor. The traces of the mean joint angular velocities are shown in Figure 2. As in Figure 1, the larger dashed vertical line represents heel strike, whereas the smaller dashed vertical lines show when the joints were flexing, extending, or hyperextending. The values for work done for the ankle, knee and hip joints during the whole stride, as well as during swing and stance, are shown in Table 1.

**** Figure 1 near here ****

**** Figure 2 near here ****

**** Table 1 near here ****

All results presented below refer to the whole group with both men and women included. Mean speed was 13.37 km·h^{-1} (± .74), stride frequency was 1.60 Hz (± .06), and stride length was 2.32 m (± 0.16), equating to a mean stride length ratio of 132.8% (± 7.6). Mean contact time was 0.283 s (± .018) and flight time was 0.030 s (± .011). The mean foot ahead ratio was 21.4% (± 1.8) and the foot behind ratio was 27.0% (± 1.3). The mean knee angle at contact was 180° (± 2), hyperextending to 185° (± 4) at midstance and flexing to 148° (± 4) at toe-off. The mean ankle angle at midstance was 106° (± 3) and the mean hip angle was 184° (± 4). The mean decrease in velocity before midstance was –0.57 km·h^{-1} (± .10) whereas the mean increase in velocity after it was 0.72 km·h^{-1} (± .11), resulting in a net change in velocity of 0.15 km·h^{-1} (± .11) and gross change in velocity of 1.29 km·h^{-1} (± .18).

Because muscle groups performed work during different power phases, Table 2 shows the total work done for each muscle group (some phases have been omitted because the total work done was very small, i.e. less than 2 J). In each case, the phases in Table 2 refer to the power bursts that occurred at the indicated positions in Figure 1. The proportional contribution of each joint to total work during stance and swing (generation and absorption) is shown in Figure 3.

**** Table 2 near here ****

**** Figure 3 near here ****

Stride frequency was associated with positive work by the ankle plantarflexors during late stance (A2 phase in Figure 1) (r = .617, P = .008) and negative work by the knee extensors during late stance / early swing (K1) (r = –.508, P = .037). The negative work performed by the knee extensors during the K1 phase was also associated with decrease in velocity (r = –.728, P = .001) and increase in velocity during stance (r = .599, P = .011), with the result that this negative work was also associated with changes in gross velocity (r = .783, P < .001). Similarly, positive work by the hip flexors during the H1 phase was associated with decrease in velocity during early stance (r = .527, P = .010), increase in velocity during late stance (r = –.636, P = .006) and change in gross velocity (r = –.689, P = .002). This power generation at the knee (K3) was also correlated with knee hyperextension at midstance (r = .685, P = .002) and foot behind ratio (r = .612, P = .009). Foot behind ratio was associated with negative work at the ankle before midstance (A1) (r = –.593, P = .012).

DISCUSSION

The aim of this study was to analyse lower limb work magnitudes and patterns in world-class race walkers. Overall, most of the positive work was done by the hip, which occurred during two main phases: the first burst of energy generation was by the hip flexors and began during late stance and continued until midswing (H1 in Figure 1); the second burst of energy generation occurred during hip extension from late swing until early stance (H3). The hip muscles are therefore the most important group in generating energy with regard to the specific demands of race walking, and this result confirmed earlier electromyography findings that the hip flexors and extensors are the key muscle groups to develop in race walking (Hanley & Bissas, 2013; Murray, Guten, Mollinger, & Gardner, 1983). However, even though the ankle's contribution to total lower limb energy generation was much smaller, the timing of its power burst supported earlier findings that the triceps surae muscles have a key role in total energy generation before toe-off (Hanley & Bissas, 2013; White & Winter, 1985). By contrast, the knee generated little energy (similar to sprinting (Bezodis et al., 2008)) and in fact was a net dissipater of energy, with noticeably large negative work produced during swing. The absorption of energy by the knee extensors during swing was an important contributor to better walking as it was associated with smaller changes in gross velocity during stance, because athletes slowed less during braking and consequently required less acceleration to maintain velocity. The knee extensors thus acted as a useful buffer that absorbed energy and allowed other structures of the lower limb to move in a way that reduced the need for energy generation by those structures. Race walkers who did more positive work at the hip from late stance into early swing also experienced smaller gross changes in velocity and required less energy generation to maintain horizontal speed, and thus the powerful hip flexion movement that occurs during this phase (H1) is an important element of race walking technique to develop.

Because of its role in foot movement, the ankle has a geometric restriction with the ground and this meant it was affected by the knee's hyperextension during stance. The ankle dorsiflexed for much of early stance but with a resulting plantarflexor moment that absorbed energy. The energy absorption by the triceps surae during this phase was succeeded by a period of considerable energy generation at the ankle during late stance, and some energy absorption also occurred at the hip. However, any negative work performed was mostly by the knee extensors, and even more so by the knee flexors from mid-swing to early stance. Because the knee flexor muscles (the hamstrings) are biarticular they have been found to contribute to the positive work performed at the hip during late swing and early stance through a transfer of energy (Hoga et al., 2003). In the present study, work has been calculated for each discrete lower limb segment, but previous research on race walking has shown that some energy will have been transferred from other segments (e.g. from the thigh to the lower leg during swing) (Hoga et al., 2003, Hoga et al., 2006) as in normal walking (Zajac, Neptune, & Kautz, 2002). The knee muscles' role as energy absorbers during the swing phase (with the hip muscles acting much more as energy generators) has also been reported for sprinting (Vardaxis & Hoshizaki, 1989), with similar patterns but much less activity during swing in normal walking (Prilutsky & Gregor, 2001). However, the knee must extend more during swing in race walking than in running (Smith & Hanley, 2013), and because it is an endurance event any resulting abnormal stress experienced by the lower limb muscles occurs repeatedly. The rules of race walking essentially mean its 'grounded' technique lies somewhere between the two ends of the gait spectrum (normal walking and sprinting) and this paper thus provides additional useful information on work patterns across human gait.

Although there are potential performance benefits of energy absorption by muscles, this comes with a risk of injury because of the high amounts of stress encountered during the concurrent eccentric action (LaStayo et al., 2003). The regions of the body most frequently injured in elite-standard race walkers are the hamstrings and knee (Hanley, 2014) and this is unsurprising given the considerable energy the knee flexors absorbed during swing (36.8 ± 5.8 J), and which is experienced approximately 20,000 times on each leg in a 50 km race. Similar injuries to the hamstrings in running have been attributed to the knee's rapid extension during swing when these muscles are also acting as hip extensors (Chumanov, Heiderscheit, & Thelen, 2011) and this is exacerbated in race walking because of the need to fully extend the knee by initial contact. Injuries to the anterior shin muscles are also frequently reported by elite-standard race walkers (Hanley, 2014), and similar to the increased stress found during fast normal walking (Prilutsky & Gregor, 2001), might be caused by the high activation of the ankle dorsiflexors during swing (Hanley & Bissas, 2013). The energy absorption by the dorsiflexors at initial contact (before the A1 phase) has been given as a possible reason for this shin pain in race walkers (Sanzén, Forsberg, & Westlin, 1986), but this might be less likely than the swing phase action given the very brief duration of energy absorption and its small magnitude (< 2 J). Regardless, it is recommended that coaches pay particular attention to the strength of their athletes' hamstrings and shin muscles to try to reduce the risk of injury.

Unlike other forms of competitive gait like sprinting, the technique adopted in race walking can only be optimised within the constraints of Rule 230.2. The mean flight time in this study was 30 ms (± 11) and thus most athletes were below the 40 ms threshold that has been reported as when judges can observe loss of contact (Knicker & Loch, 1990; Lee, Mellifont, Burkett, & James, 2013). However, longer flight times have been associated with quicker performances and increases in speed (Hanley & Bissas, 2016; Pavei & La Torre, 2015) and in this study they were also correlated with less net work, and might have reduced the muscles' energy generation requirements. Longer foot behind ratios were associated with more overall positive work and less negative work, and hence shorter foot behind distances (and longer flight times) are beneficial in both increasing speed and performing less muscular work. With regard to the second part of Rule 230.2, the mean knee angle at initial contact was 180° (± 2), hyperextending to 185° (± 4) by midstance. Although a greater degree of knee hyperextension might be beneficial with regard to conforming more obviously to the rules (to the judges' eyes), greater hyperextension of the knee at midstance was detrimental because more positive work was needed from the knee flexors to unlock the joint and allow it to flex before toe-off. This unlocking is not required in other gaits where the knee does not hyperextend and its unique action means that other forms of gait (such as distance running) might be unsuitable for developing efficient and legal race walk technique. In addition, the need to achieve a straightened knee by initial contact means the knee must extend more than in running (Smith & Hanley, 2013) and this contributes to the extended period of energy absorption during swing. Athletes and coaches should therefore be made aware that there might be energy costs with legal techniques that are overly cautious.

A key strength of this study was that all race walkers had competed at either (or both) the Olympic Games or IAAF World Championships and thus improved our understanding of the mechanics of race walking beyond that of previous studies (e.g. Hanley & Bissas, 2013; Hoga et al., 2006). With regard to future research on elite-standard race walking, measurements of the CM during the stance phase using the

GRF approach might be more suitable than using BSP data (Pavei, Seminati, Cazzola, & Minetti (2015)), especially if the study focuses to an even greater extent on kinematic variables. Furthermore, three-dimensional studies will be useful in analysing joint moments, power and work in all planes of movement and in particular with regard to the effect of the straightened knee on joint mechanics and muscle activity.

CONCLUSIONS

This was the first study to analyse the mechanical work performed by the lower limb in elite-standard race walkers. The main energy generating muscle groups were the hip extensors, hip flexors and ankle plantarflexors, with the work performed by the hip flexors during late stance and early swing particularly important as it reduced gross changes in velocity during stance. This key factor in race walking was also influenced by concurrent energy absorption by the knee extensors during the same phase of late stance / early swing. Whereas some of these findings are similar to those in running, the requirement for a straightened knee from initial contact to midstance results in an extended period of energy absorption during swing that increases the potential risk of injury, and also increases the energy requirements of the knee flexors during its unlocking phase in stance. These unique features of race walking require specific strength and conditioning programmes that emphasise legal knee motion.

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Table 1. Mean (± *s*) total work done (J) at the ankle, knee and hip joints during one complete race walking stride.

	Swing	Stance	Whole stride
Ankle (J)	1.6 (± 0.5)	5.9 (± 5.3)	7.6 (± 5.4)
Knee (J)	–49.1 (± 8.7)	–3.0 (± 4.9)	–52.1 (± 10.6)
Hip (J)	44.0 (± 10.8)	11.0 (± 10.2)	55.0 (± 12.1)

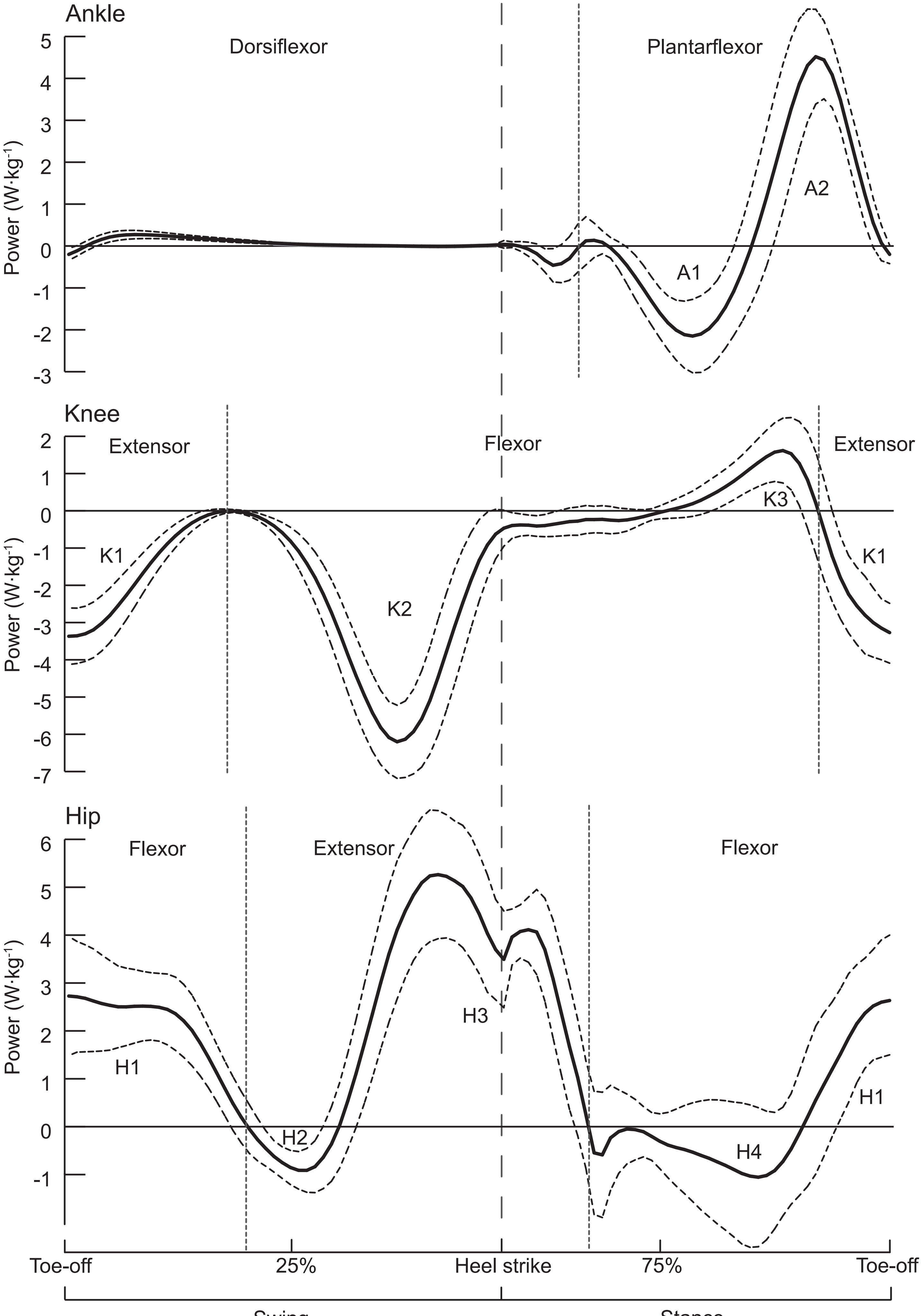
Table 2. Mean (± *s*) total work done (J) and peak power ($W \cdot kg^{-1}$) by each of the main muscle groups during either energy generation or absorption. Only those phases where the mean work total was 2 J or more have been included.

	Total work (J)	Peak power ($W \cdot kg^{-1}$)	Phase
Ankle			
Plantarflexors (absorbing)	–9.2 (± 3.3)	–2.1 (± 0.9)	A1
Plantarflexors (generating)	16.3 (± 4.3)	4.5 (± 1.1)	A2
Knee			
Extensors (absorbing)	–19.5 (± 4.8)	–3.4 (± 0.8)	K1
Flexors (absorbing)	–38.6 (± 5.8)	–6.2 (± 1.0)	K2
Flexors (generating)	6.1 (± 3.2)	1.6 (± 0.9)	K3
Hip			
Flexors (absorbing)	–6.8 (± 8.3)	–1.1 (± 1.5)	H4
Flexors (generating)	24.5 (± 6.9)	2.7 (± 1.2)	H1
Extensors (absorbing)	–3.1 (± 1.6)	–0.9 (± 0.4)	H2
Extensors (generating)	40.3 (± 8.3)	5.3 (± 1.3)	H3

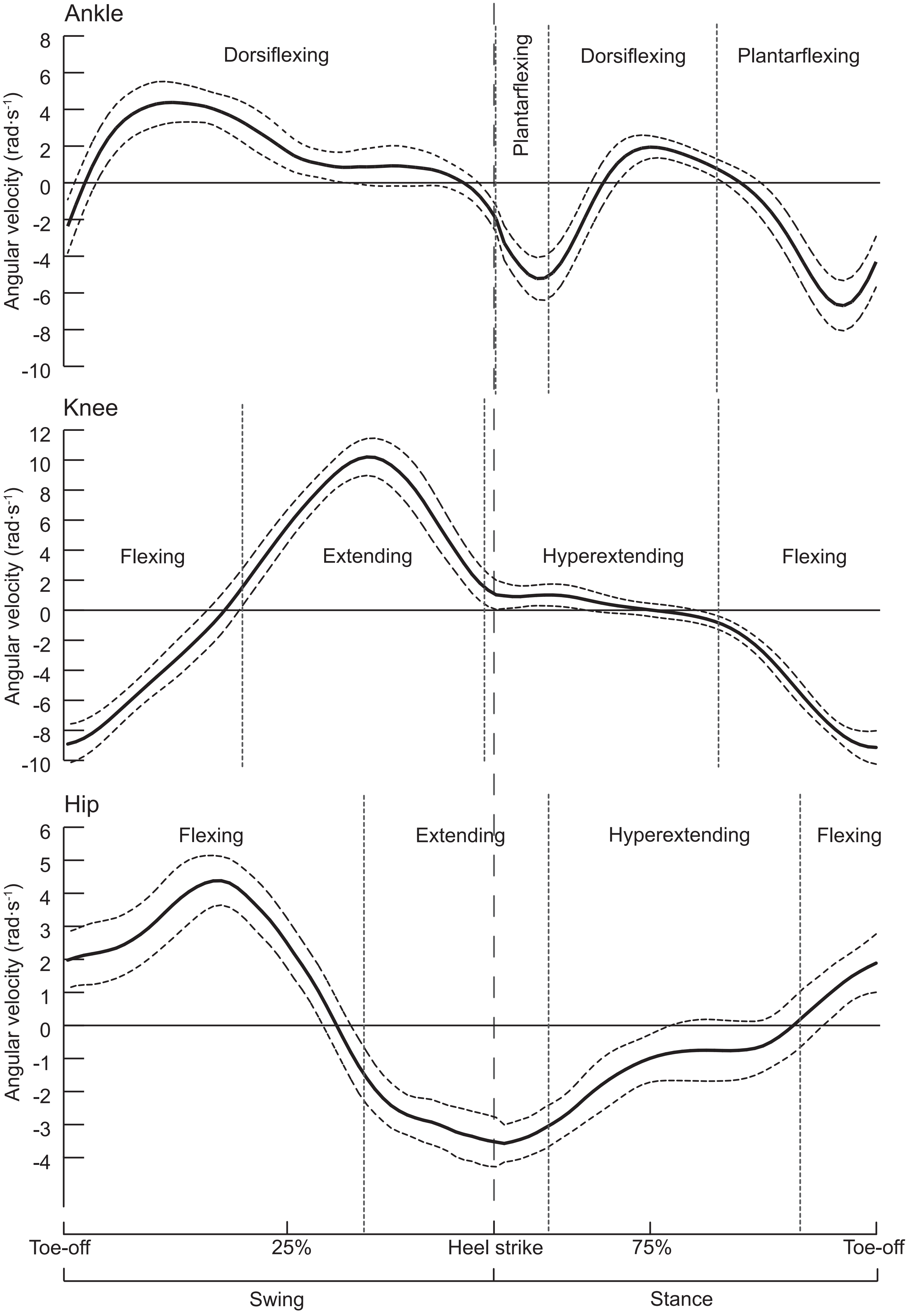
Figure 1. Mean (± *s*) power of the ankle, knee and hip joints during a race walking stride. The larger dashed vertical line represents the transition from swing to stance, while the smaller dashed vertical lines show when the net moments were flexor or extensor.

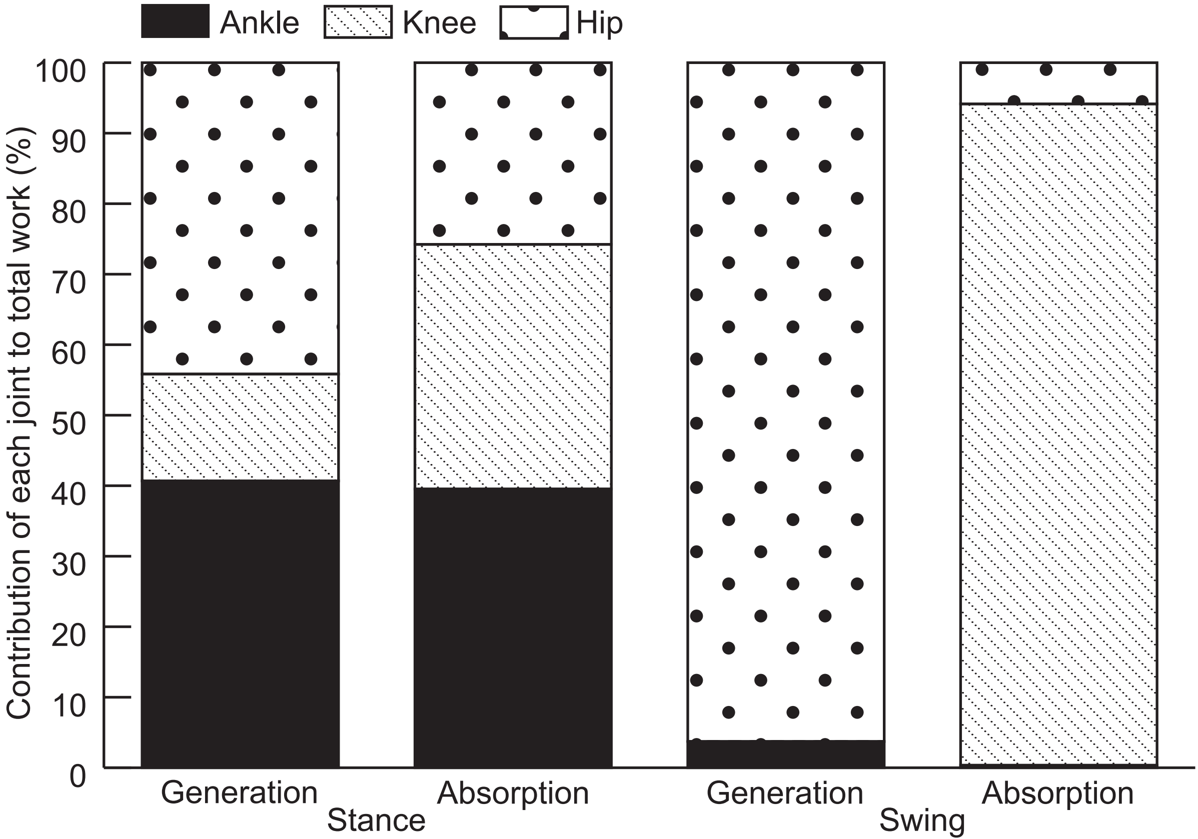
Figure 2. Mean (± *s*) angular velocity of the ankle, knee and hip joints during a race walking stride. The larger dashed vertical line represents the transition from swing to stance, while the smaller dashed vertical lines show when the joints were flexing, extending or hyperextending.

Figure 3. The mean proportional contribution of each joint to total work during stance and swing (generation and absorption).



Ankle
Dorsiflexor
Plantarflexor
Power (W·kg-1)
5
4
3
2
1
0
-1
-2
-3
A1
A2
Knee
Extensor
Flexor
Extensor
2
1
0
-1
-2
-3
-4
-5
-6
-7
K1
K2
K3
K1
Hip
Flexor
Extensor
Flexor
6
5
4
3
2
1
0
-1
H1
H2
H3
H4
H1
Toe-off
25%
Heel strike
75%
Toe-off
Swing
Stance


Ankle
Angular velocity (rad·s-1)
8
6
4
2
0
-2
-4
-6
-8
-10
Dorsiflexing
Plantarflexing
Dorsiflexing
Plantarflexing
Knee
Angular velocity (rad·s-1)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
Flexing
Extending
Hyperextending
Flexing
Hip
Angular velocity (rad·s-1)
6
5
4
3
2
1
0
-1
-2
-3
-4
Flexing
Extending
Hyperextending
Flexing
Toe-off
25%
Heel strike
75%
Toe-off
Swing
Stance


Ankle
Knee
Hip
Contribution of each joint to total work (%)
100
90
80
70
60
50
40
30
20
10
0
Generation
Absorption
Stance
Generation
Absorption
Swing