A COMPARISON OF FIVE MECHANICAL WORK ALGORITHMS FOR DIFFERENT FOOT STRIKE PATTERNS AND SPEEDS DURING DISTANCE RUNNING

M. M. Slavin, R. A. Hintermeister, J. Hamill

Biomechanics Laboratory
University of Massachusetts
Amherst, Massachusetts, USA

INTRODUCTION

The mechanical work done by a runner during an average stride cycle has been calculated using a variety of algorithms. Work values (joules•cycle-1) may vary greatly as reflected in efficiency ratios (Cavanagh & Kram, 1985). Mechanical work values from a variety of algorithms applied to the same data set are infrequently presented in the literature. In particular, this opportunity to compare algorithms does not seem to have been applied to different foot strike patterns (FSP) during distance running.

The purpose of this paper is to present average stride cycle values for five work algorithms for forefoot strike *(ffs)* and heel strike*(hs)* running at three different running speeds. The primary difference between algorithms is the amount of energy transfer they permit within and between body segments. The fundamental equation for all algorithms is:

$$W = \Delta TKE + \Delta RKE + \Delta PE$$

where TKE=translational kinetic energy, RKE=rotational kinetic energy and PE=potential energy. In general order from most to least restrictive, the algorithms are: Wn allows no transfer between segments (Norman et al., 1976); Ww, within-segment transfer only (Pierrynowski et al., 1980); WwbAS, transfer within and between adjacent segments only (Williams and Cavanagh, 1983); WwbLT, within and between segments of the same limb and the trunk (Williams and Cavanagh, 1983); and Wwb, within and between segment transfer with no restrictions (Winter et al., 1976).

METHODOLOGY

The experimental design had a total of six conditions comprised of two FSPs used at each of three different running speeds. Twelve highly skilled, male distance runners (10K/5-mile personal record pace mean = 5.07 min•mile^{-1}) were selected as either natural heel strikers (n=6) or natural forefoot strikers (n=6). Each subject performed all six conditions in a cross-over experimental design. Within each of the two groups, conditions were presented in a balanced order (Latin Square design) to minimize order effects.

The experimental setup included a 200 Hz high speed video camera with a lens-object distance of ≈ 5.5 m and line of sight level with the subject's trochanter, to collect a left sagittal view. A high-mass treadmill was used for all testing to minimize speed fluctuations (and energy exchange differences vis-a-vis overground running). A thin, contact plate footswitch mounted to the rear of the sole and wired to an LED visible to the subject was used as feedback. Heel compression resulted in illumination, required during *hs* conditions, not permitted during *ffs* conditions. Physiological energy expenditure data was collected concurrently using open-circuit spirometry and heart rate telemetry. Fingertip lactate samples were also drawn after the two fast running conditions.

The standard protocol entailed two test sessions separated by at least four days or as much time as a subject needed to fully recover from any calf muscle soreness, which had occurred post-test in natural heel strike runners using *ffs* during a pilot study. Subjects were asked to arrive rested and in a fasting state. Each condition lasted seven minutes and was preceded with ample rest. The three speeds of 4.88, 4.13 and 3.58 $m \bullet s^{-1}$ corresponded to a near-race pace (5.5 $min \bullet mile^{-1}$), a medium training pace (6.5 $min \bullet mile^{-1}$) and a slower training pace (7.5 $min \bullet mile^{-1}$) for this population. Before each session, reflective markers were placed on the following anatomical landmarks: fifth metatarsal head, calcaneus, lateral malleolus, lateral femoral condyle of the knee, greater trochanter, glenohumeral junction, lateral epicondyle of the humerus and the styloid process. The distance between markers was recorded and duplicated for the second session by the same investigator to minimize placement error. Before the initial session, each subject was classified as natural heel strike or natural forefoot strike based on several criteria: 1) evaluation of overground FSP at a comfortable pace, 2) review of sole wear on training and racing flats used only for running, and 3) (of minor importance) self-reported FSP.

Five complete left strides (TD to TD) for each condition (FSP x speed) were digitized using a Motion Analysis VP110 video processor interfaced to a SUN minicomputer. A total of thirty video records of eight paths for each subject were analyzed to derive an eleven-segment model. Paths were filtered with a fourth-order, recursive, low-pass Butterworth filter with independent x and y optimal cutoffs.

RESULTS

Actual ($joules \bullet stride^{-1}$) and speed-normalized (slow speed=100%) mechanical work values are displayed in Table 1 and Figure 1. The bar graph also contrasts the *hs* and *ffs* relative magnitudes for the different algorithms. Among the algorithms, the no-transfer method (Wn) produced the highest work estimates. An absolute difference of ≈ 300 $joules \bullet stride^{-1}$ (≈ 15-20%) existed across speeds between the no-transfer and within-transfer algorithms. There was then a relatively large decrease to the span of values generated from the other three algorithms. WwbAS was higher than the remaining two algorithms. Both WwbAS and WwbLT increased moderately over speed (≈ 50% slow->fast), while Wwb, the least restrictive, showed almost no change across speeds (≈ 1% slow->fast). WwbLT (458) and Wwb (466 $joules \bullet stride^{-1}$) had similar overall means.

On average, the differences between hs and *ffs* decreased absolutely (78 to 20 $joules \bullet stride^{-1}$) and relatively (9.0% to 1.7%) as speed increased. In other words, the two FSP "converged" as speed increased. Wwb across speeds consistently showed the largest relative differences. At all speeds for each algorithm, *hs* was lower than *ffs*. Collapsed across speeds, *hs* as a percentage of *ffs* was similar across algorithms, 95.8 to 96.7%, except for Wwb (89.4%).

DISCUSSION

The larger decrease between Ww and the three wb algorithms than from the Wn to Ww algorithm suggests more mechanical energy is conserved across joints than within limb segments. The relatively anomalous behavior of the least restrictive algorithm, Wwb, with no change over speed and attenuated
convergence between FSP with increased speed, may imply that this algorithm should be viewed differently from the others when picking a mechanical algorithm for running

analyses. It is possible energy transfer improves with increased speed enough to offset the greater amplitudes and frequencies of faster running; however, the possibility of transfer between remote limbs such as the left shank and right forearm may not be reasonable. In addition, substantial metabolic cost increases (not reported here) support this conclusion. The greater relative variability, reflected in the standard deviations (Table 1), also flags the Wwb algorithm.

Table 1. Mechanical work: Five algorithms for six conditions {2 FSP x 3 speeds} (joules•cycle^{-1}). Each cell is the average (sd) of the twelve five-trial means.

Algorithm	*hs* slow	*ffs* slow	*hs* med	*ffs* med	*hs* fast	*ffs* fast
W_n	1465.3	1579.7	1752.7	1800.5	2167.4	2186.8
	(166.9)	(140.5)	(188.9)	(198.5)	(247.5)	(251.3)
W_w	1183.7	1278.6	1442.3	1484.4	1832.8	1857.3
	(137.4)	(114.0)	(157.2)	(166.3)	(214.7)	(218.1)
W_{wbAS}	518.6	558.5	617.6	628.5	762.5	776.3
	(63.8)	(54.2)	(71.0)	(72.9)	(88.0)	(89.4)
W_{wbLT}	363.9	401.2	435.0	448.9	546.8	554.5
	(50.9)	(44.5)	(56.7)	(57.6)	(68.0)	(70.9)
W_{wb}	419.1	505.6	449.6	487.0	450.4	483.5
	(76.5)	(92.4)	(77.3)	(92.1)	(85.5)	(106.9)
Average	790.1	868.3	939.4	969.9	1152.0	1171.7

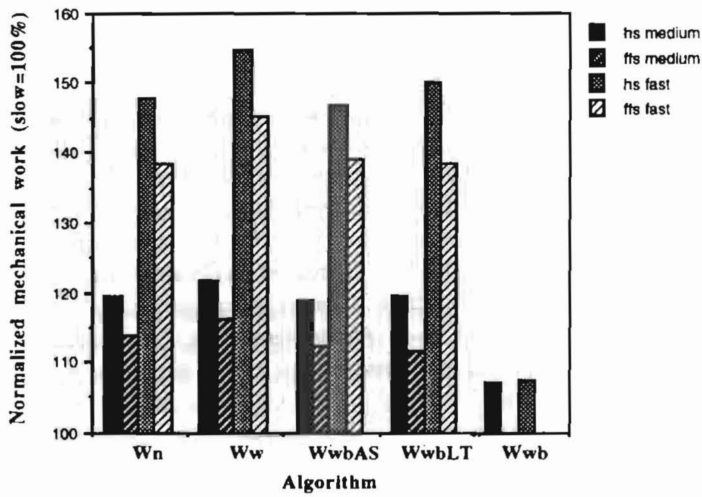

Figure 1. Mechanical work normalized to slow speed (slow=100%).

All fifteen combinations of speed and algorithm showed *hs* lower than *ffs*, with the relative difference always less with increased speed; i.e. the ordinal relationship and trend in relative change between FSP over speed was consistent. This consistency suggests kinematics, not algorithm, accounts for observed differences and that kinematics are less dissimilar at faster speeds. For the trunk and legs over speeds of 0.5 to 5.5 m•s^{-1}, within and between segment transfer were "offsetting functions of velocity" implying the relative contributions changed in opposite directions (Caldwell et al., 1989), a confounding factor not directly analyzed here, and worthy of further investigation. Cavagna et al. (1964), allowing energy transfer, found total mechanical work per stride was constant, while Kaneko et al. (1985) concluded it increased exponentially with speed (4.0 to 9.5 $m \bullet s^{-1}$). All but the Wwb algorithm here support the latter conclusion.

CONCLUSIONS

The *hs* FSP appears to generate lower mechanical work values then *ffs* per stride cycle for five different work algorithms that differ in the amount of inter- and intra-segmental energy transfer allowed. The *hs-ffs* differences consistently decrease in absolute and relative terms with increased speed. The least-restrictive algorithm, Wwb, exhibited not only the lowest values overall but different relative behavior and variability across speeds and FSP than the other algorithms.

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