CHANGES IN MECHANICAL WORK AND JOINT CONTRIBUTIONS OF THE LOWER LIMB JOINTS DUE TO FATIGUE IN DISTANCE RUNNING

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The purpose of this study was to investigate changes in work, and joint contributions by the lower limb joints in response to fatigue in distance running and to obtain insight into maintaining the running velocity. Fifteen male distance runners ran a 4000 m trial in even pace. Running motion and ground reaction force were collected each lap and two-dimensional inverse dynamics were performed to calculate the lower limb joint torques, powers and work in the initial, middle and final stages of the trial. The joint contributions of the lower limb joints represented the ratio of the work of each joint to the total mechanical work. Results indicated that the mechanical work and joint contribution did not change significantly from the initial to the final stages of the trial. The joint with the largest contribution decreased the joint contribution from the middle to the final stage, although these changes varied runner by runner. It was concluded that the lower limb joints could compensate each other to maintain the total work output during the trial.

KEY WORDS: distance running, fatigue, mechanical work, effectiveness, joint contribution.

INTRODUCTION: It is known that the technique of distance runners changes due to fatigue. However, previous studies have suggested that changes in the running technique are different from one runner to another, running condition (e.g. track or treadmill) and running speed (Elliot and Ackland, 1983; Williams *et al.*, 1991). Hubley and Wells (1983) and Ae *et al.* (1990) suggested that mechanical work and the contribution of the lower limb joints would be useful variables to investigate in sports skill. Although it was reported that mechanical power and work in the lower limb joints increased as a running velocity increased (Ae *et al.*, 1986), there was no information about the changes in mechanical work of the lower limb joints when a runner was fatigued. The purpose of this study was to investigate changes in mechanical work and the contribution of the lower limb joints in response to fatigue in distance running and to obtain insight into how distance runners maintain running velocity.

METHODS: Fifteen male competitive distance runners, whose 5000 m personal best time ranged from 13 min 52 s to 16 min 39 s, ran a 4000 m trial one at a time in even pace, with the pace based upon the 5,000 m personal best time of each subject. The bike led the runner in order to keep his pace. Ground reaction force data (GRF) were measured every lap (total 9 laps) at 500 Hz with two force platforms (Kistler) mounted in the running track. Runners practiced sufficiently to strike the force platforms before the trial and a mark was set in 10 m front of the platforms in order to adjust the foot displacement. The motion over one running cycle was videotaped from the lateral of the runner at 250 Hz with a high speed video camera ($HSV\text{-}500C^3$, Nac). A LED signal was used to synchronize the GRF data with the VTR image. Two dimensional coordinates of 23 body land marks were obtained by digitizing VTR images in the initial, middle and final stages of the 4000 m trial. The coordinate data were smoothed by a fourth-order Butterworth digital filter at 2.5 – 6.75 Hz, which was decided for each point by residual analysis. Moreover, Masses, center of mass locations and moments of inertia of the body segments were estimated from the body segment parameters after Ae *et al.* (1992). Joint torque at the hip, knee and ankle was calculated by an inverse dynamic approach using three rigid body model representing the foot, shank and thigh. Mechanical work at the hip, knee and ankle was calculated by integrating the joint torque power, which was an inner product of the joint torque and the joint angular velocity. The contribution of these joints (joint contribution) was the ratio of the mechanical work of each joint to the total mechanical work of three joints. In order to investigate changes in contribution of three joints contribution of each joint was calculated to subtract the joint contribution of the initial stage from the middle stage (I-M) and that of the middle stage from the final stage (M-F). Mean power was calculated by dividing the mechanical work by a cycle time. Effectiveness index of mechanical energy utilization to running velocity (EI) was calculated by dividing translational mechanical energy of the body by the total mechanical work of the lower limb joints. Differences among the three stages were tested using a within-subject, repeated measured ANOVA. The level of statistical significance was set at 5 %.

RESULTS AND DISCUSSION: The time of the 4000 m trial was 12 min 19 ± 28 s. Table 1 shows changes in running velocity, step length, step frequency and time of each phase in running cycle. First and second half of the support phases were divided by a time that center of mass of a body passed just above the ball of the support foot. There were significant decreases in the running velocity and step frequency. The time of the first half of the support time increased significantly, but the non-support time did not change. These changes were more significant from the middle to the final stage. Table 2 shows changes in mechanical work, mean power and effectiveness index of mechanical energy utilization to running velocity (EI).

Table 1 Mean values of running velocity, step length, step frequency and time of each phase in running cycle in the initial, middle and final stage of the 4,000 m trial.

		Initial (I)	Middle (M)	Final (F)	Difference
Running velocity	(m/s)	5.78 (0.29)	5.63 (0.29)	5.40 (0.29)	I>M>>>F
Step length (SL)	(m)	1.75 (0.09)	1.73 (0.08)	1.70 (0.06)	
Step frequency	(step/s)	3.32 (0.15)	3.25 (0.15)	3.17 (0.16)	I>M>>>F
Support time	(s)	0.159 (0.013)	0.164 (0.009)	0.171 (0.009)	I,M<<<F
First half of support time	(s)	0.072 (0.007)	0.078 (0.006)	0.082 (0.006)	I<<<M<<<F
Second half of support time	(s)	0.088 (0.008)	0.086 (0.005)	0.089 (0.005)	
Non-support time	(s)	0.143 (0.013)	0.144 (0.012)	0.146 (0.012)	

Value shows mean (SD). N=15 < p<0.05, << p<0.01, <<< p<0.001

Table 2 Mean values of energetic parameters in the initial, middle and final stages of the 4,000 m trial.

		Initial (I)	Middle (M)	Final (F)	Difference
Mechanical Work	(J/kg)	5.54 (0.58)	5.65 (0.73)	5.61 (0.76)	
Mean power	(W/kg)	9.19 (0.99)	9.18 (1.26)	8.89 (1.41)	
EI		3.03 (0.23)	2.84 (0.35)	2.63 (0.31)	I>M>F

Even if there was no significant change in the mechanical work and power, EI decreased significantly from the initial to the middle and final stages. Knicker and Arampatzis (1995) reported that although running velocities were similar in the middle and final stages of the 10000 m race, the runners increased their mechanical work to maintain the running velocity in the final stage of the race. These facts suggested that distance runners could maintain levels of mechanical work and power during a race regardless of fatigue, but they decreased EI during the race, which indicated a change in the running technique when fatigue. Mean values of joint contributions of the hip, knee and ankle joints to the total mechanical work were 38.4, 39.4 and 22.3% in the initial stage, 40.3, 37.3 and 22.4% in the middle stage, and 39.5, 37.9 and 22.6 % in the final stage. There was no significant change in the joint contributions among the stages of the trial. As a result of classifying the runners according to size order of joint contribution in three joints, two types were found: (i) a hip-knee-ankle type in which the large joint contribution was from the hip joint and (ii) a knee-hip-ankle type in which the largest was the knee joint. The number of runners displaying the hip-knee-ankle strategy was 6, 10 and 10 in the initial, middle, and final stages, and the number displaying the knee-hip-ankle strategy was 9, 5 and 5. The hip-knee-ankle strategy and the mean hip joint contribution increased from the initial to the middle stage, although no significant difference was evident. Ae *et al.* (1986) indicated that the contribution to mechanical work of the hip joints increased with increasing effort or the total work in vertical jumping, landing and running. Therefore, it is suggested that the hip joint was an important contributor to the mechanical work in distance running. Figure 1 shows typical changes in the joint contribution of the hip, knee and ankle joints during the 4,000 m trial (9 laps). Missing data were the force platforms because of subjects failing to strike. Subject A showed a large hip joint contribution in the initial stage, but he gradually decreased it and increased his knee joint contribution in the middle stage. Subject B showed a relatively large knee joint contribution in the initial stage, and he gradually decreased his knee joint contribution while he increased his ankle joint contribution in the middle and final stages. These results indicate that as one joint contribution increases, the other joint contributions decrease to wards the end of the trial, although those changes were different in the runners.

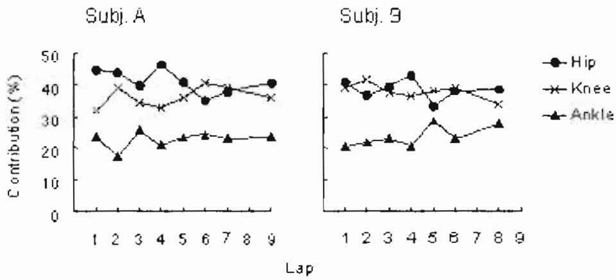

Figure 1. Typical changes in the joint contributions of the hip, knee and ankle joints during the 4000 m trial (9 laps).

Figure 2 shows the relationship between the joint contribution and Δ contribution in the initial and middle stage. Although there was no significant relationship between the joint contribution and Δ contribution I-M in the initial stage of the trial, significant negative relationships were found between the joint contribution andΔcontribution M-F in all three joints in the middle stage of the trial.

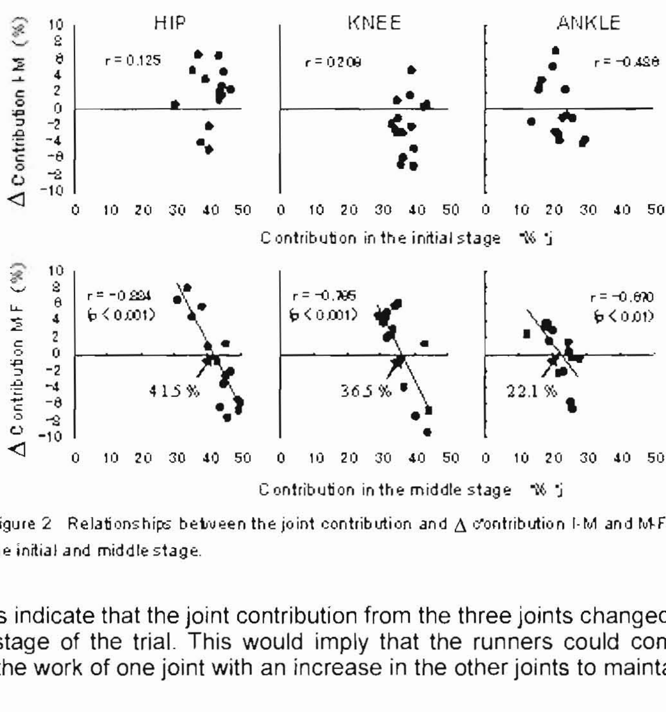

Figure 2 Relationships between the joint contribution and Δ contribution I-M and M-F in the initial and middle stage.

These results indicate that the joint contribution from the three joints changed from the middle to the final stage of the trial. This would imply that the runners could compensate for the decrease in the work of one joint with an increase in the other joints to maintain the total work done in the case of feeling fatigue. Furthermore, it is worth noticing that the intersection between the regression lines and the x axes were 41.5, 36.5, and 22.1% at the hip, knee and ankle joints, respectively. These ratios of the three joints may indicate the joint contributions which are not changed due to fatigue in order to keep the running technique. These findings suggest that monitoring joint contributions will be useful when evaluating the technique of distance runners attempting to maintain the running velocity.

CONCLUSIONS: The results revealed that the work and mean power of the lower limb joints did not change remarkably, although effectiveness of mechanical energy utilization decreased from the initial to the final stage. The joint with the largest contribution decreased the joint contribution from the middle to the final stage, although these changes varied from runner to runner. It was concluded that the lower limb joints could compensate each other to maintain total work output. It is suggested that further research should evaluate the technique of distance runners using the joint contribution to assess efficiency in maintaining the running velocity.

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