TRAINING FAVORS THE FORWARD PROGRESSION DURING HUMAN LOCOMOTION.

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The purpose of this study was to test if the mechanical locomotion technique was linked to training. To this end we calculated the different kinetic energies ratios to the total kinetic energy in three groups (untrained, sprinter and endurance-trained men) during walking and running on a treadmill. It appeared that walking was distinguished from running by higher translational body segments movements in the sagittal plane. Moreover training was necessary to favor the forward progression by minimizing interference movements at all walking and running speeds.

KEY WORDS: walking, running, kinetic energy, training.

INTRODUCTION: Different forms of energy are essential when dealing with the performance of human locomotion: on the one hand, metabolic energy that reflects the energetic expenditure during exercise on the other hand mechanical energy that makes the body move. The locomotion technique was studied by estimating the mechanical energy and the internal work during the exercise. However, it was difficult to dissociate groups of different training (Kyröläinen *et al.*, 1995) by using average values of mechanical energy. Moreover, the total kinetic energy is composed of different parts. If no difference appeared between subjects in these average values, the part of each kinetic energy composing the total kinetic energy was not as necessary. We propose the study of the different kinetic energy contributions to the total kinetic energy in trained and untrained groups.

METHODS: We propose the study of ratios between the different kinetic energies and the total kinetic energy during human locomotion on a treadmill. Fifteen subjects were divided in three groups in relation with their training specificity: untrained (UNT), sprinter (SP) and endurance-trained (END) groups. Each subject was asked to walk at five different speeds (0.98, 1.53, 2.08, 2.36, 2.64 $m.s^{-1}$) and to run at six speeds (1.53, 2.08, 2.36, 2.92, 3.88, 4.44 $m.s^{-1}$). Kinematic data were measured with a VICON370 system (Oxford Metrics, UK) composed of seven 60Hz infrared cameras and a set of spherical markers. The frequency of cameras is sufficient to give an accurate estimation of data during locomotion at these jet speeds. During the development of the exercise, 24 markers were placed over standardized anatomical landmarks in order to follow the motion of the body segments. The human body was modeled as eleven rigid linked bodies. Kinematic data were used to estimate the kinetic energies involved in human locomotion. The total kinetic energy (E_K) is the sum of the kinetic energy of the center of mass (E_{KCM}), the translational (E_{TK}) and the rotational (E_{RK}) kinetic energies of the body segments:

$$E_K = \frac{1}{2} M V^2_{G/R_T} + \sum_{i=1}^{11} \left[\frac{1}{2} m_i V^2_{G_i/R^*} + \frac{1}{2} I_i w_i^2 \right] \quad [J]$$

where M is the mass of the body and V_{G/R_t} is the linear velocity of the center of mass (G) in the frame linked to the treadmill $R_t(O',\vec{i},\vec{j},\vec{k})$ in translation with the global frame $R(O,\vec{i},\vec{j},\vec{k})$, m_i is the mass of the i[th] segment and V_{G_i/R^*} is the linear velocity of each segment center of mass G_i in the frame $R^*(G,\vec{i},\vec{j},\vec{k})$; I_i and w_i are respectively the inertial matrix and the angular velocity of the i[th] segment. The first term of this equation is E_{KCM}, the second and the third terms are respectively the translational and rotational kinetic energies (E_{TK} and E_{RK}). Ratios between kinetic energies (E_{KCM}, E_{TK}, E_{RK}) and the total kinetic energy (E_K) were computed for each subject. They were expressed as a percentage of the total kinetic energy :

$$\%E_{KCM} = \frac{E_{KCM}}{E_K} * 100 \qquad \%E_{TK} = \frac{E_{TK}}{E_K} * 100 \qquad \%E_{RK} = \frac{E_{RK}}{E_K} * 100 \quad [\%]$$

We studied the effect of the speed and the training on these ratios.

RESULTS AND DISCUSSION: Ratios are changing with the speed. Kinetic energy ratios are presented in the Table 1. Standard deviations were very small and did not exceed the value of 0.60%.

Table 1. Average values of the kinetic energy ratios.

[m.s^{-1}]		$\%E_{KCM}$		[m.s^{-1}]		$\%E_{KCM}$	
speed	Untrained	Sprinter	Endurance	speed	Untrained	Sprinter	Endurance
0.97	49.96	46.86	44.17	1.53	61.87	59.34	57.65
1.53	46.65	44.70	42.21	2.08	61.86	59.08	59.36
2.08	44.72	43.05	42.08	2.36	61.17	61.23	58.27
2.36	43.14	40.92	40.97	2.92	60.65	61.41	58.57
2.64			39.63	3.88	60.47	61.91	59.27
				4.44		61.03	56.67
[m.s^{-1}]		$\%E_{TK}$		[m.s^{-1}]		$\%E_{TK}$	
speed	UNT	SP	END	speed	UNT	SP	END
0.97	47.51	51.51	54.11	1.53	37.02	39.45	40.86
1.53	51.21	53.87	56.19	2.08	37.15	40.02	39.35
2.08	52.39	55.64	56.69	2.36	37.72	37.85	40.47
2.36	55.38	57.77	57.8	2.92	38.26	37.76	40.31
2.64			58.87	3.88	38.57	37.30	39.78
				4.44		38.21	42.28
[m.s^{-1}]		$\%E_{RK}$		[m.s^{-1}]		$\%E_{RK}$	
speed	UNT	SP	END	speed	UNT	SP	END
0.97	2.53	1.64	1.72	1.53	1.11	1.21	1.50
1.53	2.14	1.43	1.60	2.08	0.99	0.90	1.29
2.08	2.89	1.30	1.23	2.36	1.12	0.92	1.27
2.36	1.48	1.30	1.21	2.92	1.09	0.83	1.12
2.64			1.50	3.88	0.97	0.78	0.96
				4.44		0.75	1.05

As walking speed increased, the $\%E_{KCM}$ decreased and the $\%E_{TK}$ increased. Thus, the higher speed, the higher translational body segments movements. These ones were performed in order to translate the body in the forward direction. The forward direction was defined as the body displacement in the longitudinal direction. Indeed, Bianchi's study (1998) showed that the major component of the translational kinetic energy was the part due to the movements in the forward direction, which accounted for about 95% of the total translational kinetic energy. As speed increased, the translational movements were performed with a higher frequency (Nilsson *et al.*, 1985, Van Emmerik *et al.*, 1996) and with a longer stride length (Larsson *et al.*, 1980). Thus, stride length and frequency increases were associated with the increase in $\%E_{TK}$. This walking technique was confirmed by the reduction of the center of mass oscillations (calculated thanks to the 3D kinematic data) with increasing speed. In order to walk at the imposed speeds, subjects had to favor the energy of forward progression (in the longitudinal direction) in spite of the vertical displacement linked to the center of mass kinetic energy. For trained subjects, the $\%E_{RK}$ decreased with the increasing speed up to speed of 2.36 m.s^{-1}. Thus, these subjects reduced their body segments rotations to privilege their energy of progression. Moreover, previous studies showed that the main part of the rotational kinetic energy was due to the lower limbs rotations (Winter, 1976). Hence the rotations of body segments should be principally affected around the transverse axis, and rotational movements around the longitudinal and vertical axis should be reduced to the minimum. In a different way, for UNT group, even if the $\%E_{RK}$ has a general decrease when speed increases, fluctuations appeared in the $\%E_{RK}$ values between two successive speeds. Thus, the displacement technique of UNT group was different from trained subjects. UNT group adapted its body segments movements without using a specific technique. When running, untrained and trained groups adapted their kinetic energy ratios in a different way. So $\%E_{KCM}$, $\%E_{TK}$ and $\%E_{RK}$ for trained groups fluctuated between each running speed but there was no clear tendency. On the contrary, $\%E_{KCM}$ for the UNT group decreased with the increasing speed whereas the $\%E_{KT}$ increased. The $\%E_{RK}$ fluctuated between each running speed for the three groups. For the untrained group, the increase of the running speed was associated to a decrease of the center of mass vertical oscillations and an increase of translational body segments movements. During the exercise running, stride length was increased for low speeds whereas stride frequency was increased for high speeds (Nelson *et al.*, 1992). The behaviour of the lower limbs at low running speeds was linked to the translational body segments movements. This explained the increase of $\%E_{KT}$ with the increasing running speed. For each walking and running speed, we compared the different ratios of each group. For each walking speed the $\%E_{KCM}$ was always greater for untrained subjects than for trained ones. For walking speeds from 0.97 to 2.08 $m.s^{-1}$ SP showed a higher $\%E_{KCM}$ than END. These two groups had similar $\%E_{KCM}$ at the walking speed of 2.36 $m.s^{-1}$. During the walking exercise the $\%E_{TK}$ of the UNT group was the lowest. The SP $\%E_{TK}$ was always lower than the END one for speeds from 0.97 $m.s^{-1}$ to 2.08 $m.s^{-1}$. The $\%E_{TK}$ were equal for SP and END groups at the walking speed of 2.36 $m.s^{-1}$. These results distinguished the different groups among themselves. Moreover we showed in the previous part of this study that the walking technique was linked to the ability to execute body segment movements preferentially in the sagittal plane and to reduce in the same time the center of mass oscillations. Moreover, UNT group performed a center of mass oscillations which was greater than trained groups and the translational body segments was lower than in trained groups. This result was confirmed by previous study by Kyröläinen *et al.* (1995). Thus, an essential difference between untrained and trained subjects is that the trained subjects tried to reduce their center of mass oscillations to the minimum in order to favor their forward energy of progression. However, UNT subjects had forward body segments displacements less wide and less fast than the trained ones and so their center of mass oscillations less reduced. These results were confirmed by the fact that $\%E_{RT}$ of the untrained group was largely greater than the trained groups ones during the walking exercises except at a speed of 2.36 $m.s^{-1}$. The translational and rotational body segments movements are linked each other. Indeed translational body segments movements can only be performed by using the rotations of the body segments around the anatomic axes. Thus, the $\%E_{TK}$ of the untrained group which smaller than for the trained ones should imply a $\%E_{RK}$ smaller too. However, $\%E_{RK}$ acted in an opposite way. In order to favor the forward displacement, rotational movements should be executed around the transverse axis. Values of $\%E_{TK}$ were lower and of $\%E_{RK}$ were greater in the UNT group than in trained ones. This showed that additional rotations were executed around the vertical and longitudinal axes. These additional body segments movements were linked to a walking technique less-performance. During the running exercise, the behaviours of UNT and SP groups were opposite. For low speeds from 1.53 to 2.08 $m.s^{-1}$ UNT group had a greater $\%E_{KCM}$ and a lower $\%E_{TK}$ than SP group. For running speeds from 2.92 to 3.88 $m.s^{-1}$, SP group had a greater $\%E_{KCM}$ and a lower $\%E_{TK}$ than UNT group. END group, except at a running speed of 2.08 $m.s^{-1}$, showed a lower $\%E_{KCM}$ and a greater $\%E_{KT}$ than other groups. Except for the running speed of 1.53 $m.s^{-1}$, the $\%E_{RK}$ was the greatest for the END group. Thus, for low running speeds (1.53-2.08 $m.s^{-1}$) the displacement of the UNT subjects compared to others groups was first linked to the center of mass displacement. At a great running speed, body segments movements favored their forward displacement. SP performed a contraire technique. The running technique appeared different between groups in relation to their training specificity. As for walking, END group was the one that exploited the most the translational body segments movements in order to favor first the forward displacement. Then UNT and SP groups were dissociated in relation to the running speeds. Even if the increasing running speed was linked to a decrease in the center of mass oscillation for the untrained group, this one showed, as for walking, a less ability than endurance-trained and sprinters groups (at low speeds) to execute this technique.

CONCLUSION : These results showed that walking was performed by executing translational body segments movements and was linked to the forward displacement in the sagittal plane. This technique was related to the training. Moreover untrained subjects had higher center of mass oscillations and rotational movements than trained ones. Trained subjects, opposite to untrained ones, favored their progression energy by minimizing interference movements. Running was performed in the same way than walking for untrained group but as for walking, untrained subjects had higher center of mass oscillations than trained groups. That implied a lower performance than for trained subjects. Thus, the training (sprint or endurance training) favored the high-performance of the walking or running technique by minimizing lost of the energy due to interference movements of the center of mass oscillations and rotational body segments movements. However, further studies should be done in order to test the behavior of trained subjects at higher speeds than in this study to test if the changes in their energy ratios are similar at high speeds. To sum-up, these results show that even if it seemed difficult to dissociate groups of different training (Kyröläinen *et al.*, 1995) by computing average values of mechanical energies, some differences could be emphasized with our method. Hence, it is possible to discriminate trained and untrained people by measuring ratios of energy, as described in this paper. Future works are necessary to understand if these differences are enough to follow an athlete along his career, by coupling metabolic and mechanical evaluations. Nowadays only metabolic measurements are traditionally carried-out, but mechanical evaluation should bring athletes with new data concerning his performance and training.

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