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Ergonomic effects of load carriage on energy cost of gradient walking

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Abstract

We examined the effects of load on the energy cost of walking (C_w), being defined as the ratio of the 2-min steady-state oxygen consumption to the speed, and economical speed (ES) during level and gradient walking. Ten men walked on a treadmill at various speeds with and without a load on their back at 0% and $\pm 5\%$ gradients. Significantly lower C_w values were observed only when the load was carried on the back during level walking at slower speeds. The ES was significantly decreased by less than 5% when the load was carried on the back. Significant gradient differences were also observed in the ES in the load and no load conditions. These results would be applicable to a wider range of occupational and leisure tasks.

Keywords: Optimal speed; *Free-ride*; Locomotion

1. Introduction

Recent studies revealed that the energy expenditure during walking with load does not always increase linearly as a function of the carrying weight (Abe et al., 2004; Stuempfle et al., 2004). Charteris et al. (1989a, b) and Maloiy et al. (1986) have proposed a '*free-ride*' hypothesis that the energy expenditure during walking with load carried on the head does not necessarily increase in African women if the load is less than 20% of their body mass. Recently, a similar phenomenon to the *free-ride* was also found in Nepalese porters (Bastien et al., 2005a, b).

In relation to such an energy-saving phenomenon during walking with load, it was worth noting that the load was always carried on the upper part of the body, such as on the head (Bastien et al., 2005a; Charteris et al., 1989a, b; Maloiy et al., 1986) and on the back (Abe et al., 2004; Stuempfle et al., 2004). Another point in common in previous studies was the fact that such a phenomenon was observed at slower walking speeds only. Thus, Abe et al. (2004) pointed out that a similar phenomenon to the *free-ride* could be found only when the load was carried on the back at slower walking speeds, and further suggested that an interaction between the rotative torque functioning around the center of body mass and an excessive burden on the lower leg muscles comprehensively affected the energetics of walking (Fig. 1). If a similar phenomenon to the *free-ride* can be found not only during level walking but also during gradient walking, then the practical benefit will be applicable to a wider range of occupational and leisure tasks. Indeed, as recently discussed by Bastien et al. (2005b), the argument with regard to the energetics of gradient walking with load is still open. We hereby hypothesized that a phenomenon similar to the *free-ride* could be found not only during level walking but also during gradient walking, because the possible explanation for a similar phenomenon to the *free-ride* proposed by Abe et al. (2004) appeared to be independent of the gradient of the terrain. The first purpose of this study was to examine whether a similar phenomenon to the *free-ride* would be found not only during level walking but also during gradient walking.

It has been reported that there exists a specific walking speed that can minimize the metabolic energy cost of walking per unit distance (C_w: ml/kg/m) in each person (Saibene and Minetti, 2003). The walking speed corresponding to the minimum energy cost per unit distance has been called the economical speed (ES) or optimal speed

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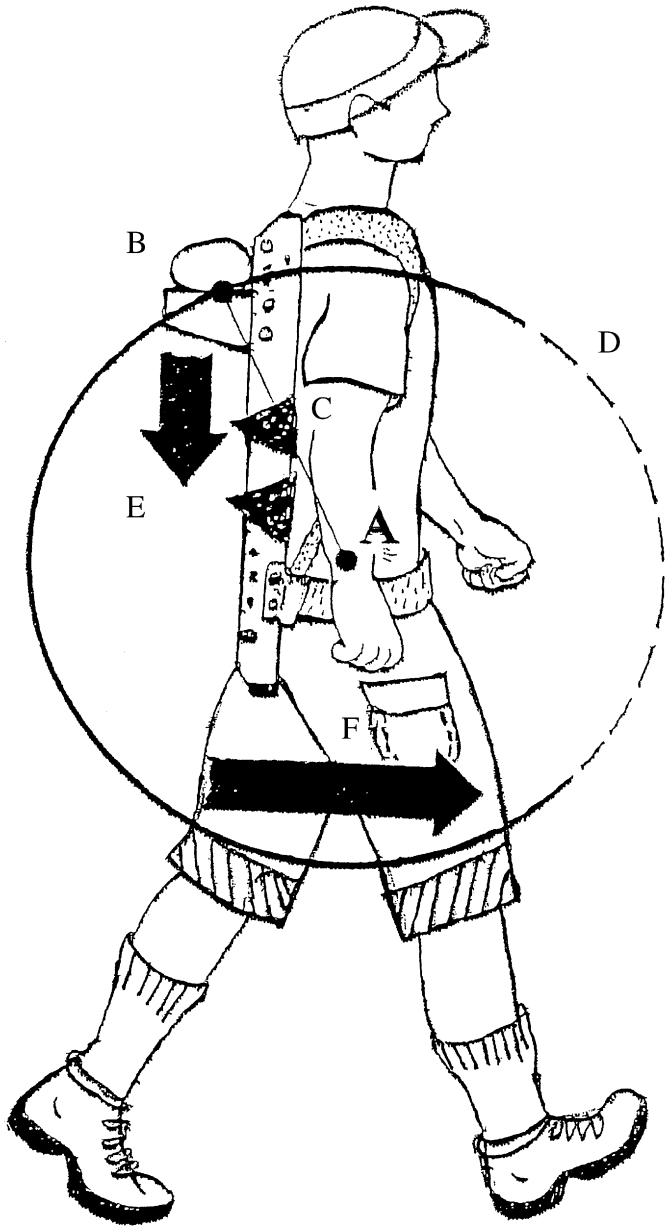

Fig. 1. A schematic description of an interaction between the rotative torque functioning around the center of the body mass (BM) and the excessive burden on the leg muscles during level walking with load on the back. (A) center of BM; (B) center of mass of load; (C) radius of rotation; (D) rotation arc; (E) excessive burden on the leg muscles; (F) rotative torque functioning around the center of BM.

(Falola et al., 2000). With reference to the ergonomic implications, considerations of ES seems to be significant for an establishment of workers' safety and for a reduction of workers' physical stress, however, as far as we know, no information has been available with respect to the alteration of the ES between level and gradient walking with load. It was interesting to note that the ES was significantly decreased if the load was carried on the back on a flat terrain (Falola et al., 2000), but was not decreased in another study (Bastien et al., 2005b). In a previous study the energy cost of walking reached minimum at a −10% gradient (Margaria, 1938). Minetti et al. (2003) indicated that the ES decreased as a function of positive gradient, but the load was not carried in those previous studies. Here, it was also hypothesized that the ES obtained from each gradient would be slower in the load condition than in the no load condition. However, it was assumed that the percentage decrease in the ES during level and gradient walking with load would not be great so much when compared to the '15%' load of the subjects' body mass, if a similar phenomenon to the *free-ride* appeared not only during level walking but also during gradient walking with load. Therefore, the second purpose of this study was to examine the effects of load carriage on the ES during level and gradient walking.

2. Methods

2.1. Subjects

Ten healthy male subjects participated in this study. The physical characteristics of those subjects were 169.9 ± 3.9 cm and 60.5 ± 3.0 kg for body height and body mass, respectively. The average age of the subjects was 20.8 ± 1.1 years old. After being informed of the purpose and possible risks of this study, a written informed consent was obtained from each subject. An approval from the ethical review committee was also obtained for all procedures.

2.2. Experimental set-up and measurements

All exercise tests were performed on a motor-driven treadmill (Biomill BL-1000, S & ME, Tokyo). To become accustomed to the treadmill walking wearing a gas collection mask (AMA-102, Minato Medical Science Co. Ltd., Osaka) with and without load, each subject performed at least two preliminary trials on the same treadmill at several speeds. The walking speeds were set at 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 m/min, meaning that the employed walking speeds covered with those of the previous studies (Abe et al., 2004). As suggested by Minetti et al. (1993), the mechanical work done by the leg muscles consisted of both positive and negative muscular work up to a 15% gradient, however, the C_w expressed per unit of vertical distance seemed to be non-linear in the 5–15% gradient zone. It was assumed that either the positive or negative work was no longer functional at more than $\pm 10\%$ gradient. Thus, the treadmill gradient was set at 0% (level), +5% (uphill) and −5% (downhill) due to a consideration of the practical application for daily activities in this study.

In all conditions, each subject walked on the treadmill for 5-min with a freely chosen step frequency at each walking speed with and without load. The subjects wore underwear, shirts, socks, gym shorts and lightweight training shoes. The measurements were performed once a day on each subject. The load consisted of a sand bag on a