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Short communication

Walking pattern efficiency during collective load transport

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ABSTRACT

Background: While the locomotor behavior of humans walking alone has been extensively studied, the locomotor behavior of humans transporting a load collectively is very poorly documented in the biomechanics literature. Yet, collective transport could find potential developments in other domains such as rehabilitation and robotics.
Research question: If collective load transport is made economically one could expect that the center of mass of the ensemble formed by several individuals and the load they carry has the same pendulum-like behavior as a single individual walking alone. The main objective of our study was to assess to what extent this is the case.
Methods: We recorded the 3D kinematics of movement of the body segments of ten dyads formed by two persons carrying a load together in three successive trials. The individuals carried the load, side by side, along a 13 m straight trajectory. Then, the recovery rate of the center of mass of the ensemble formed by the two individuals and the load they carry (i.e. the rate of transfer between potential and kinetic energy) was computed.
Results: The values of recovery rate were similar to those found in the literature for individuals walking alone, showing that the external energetic exchanges occurring during collective transport are as efficient as those occurring in single gait. The recovery rate also increased in successive trials, suggesting an improvement of the performance with familiarization.
Significance: Our results demonstrate the ability of humans to collaborate efficiently for carrying a load. The values of recovery rate we found could be used as a benchmark for the control of collaborative robots.

1. Introduction

The development of robots to assist humans in factories, hospitals and at home has become an important issue in ergonomic engineering [1]. Surprisingly, although research on human biomechanics is often used as a basis for robotic development [2], only few studies have been published so far on the biomechanical interactions between humans and robots during collective load carriage [3]. As a first step to understand the nature of these interactions, we thus decided to investigate the mechanical economy achieved by humans during a collective load carriage task.

The concept of mechanical economy has mostly been studied so far in single gait of unloaded individuals. It is based on the work by Cavagna et al. [4] who suggested that the low mechanical work achieved during walking in humans could be explained by the pendular displacement of the center of mass of the body leading the authors to model the body as an inverted pendulum system (IPS). Because it is pendular and thus induces a transfer between potential and kinetic energy along the walking cycle, the spontaneous walking pattern is considered as an efficient means of locomotion [4,5]. One had to wait the work of Heglund et al. [6] on African women for the first study on the effect of load carriage on the mechanical economy of walking. However, these authors worked on single individuals and did not extend their study to collaborative load transport, which is likely to affect walking in a very different manner.

In this study, we investigated whether two human individuals transporting an object collectively behave economically. We computed the center of mass (CoM) of the ensemble formed by a dyad of individuals and the load they carry. Then, we studied its displacement during a whole walking cycle at constant speed. High-resolution 3D tracking and reconstruction techniques of kinematic data [7] of the dyads allow to do this by representing each dyad as a Poly-Articulated Collective System (PACS), i.e. a poly-articulated system of multiple n rigid segments [8]. If the CoM displacement of the PACS has the same pendulum-like behavior as the CoM of a single individual as described in the literature, the external work would be minimal for a constant

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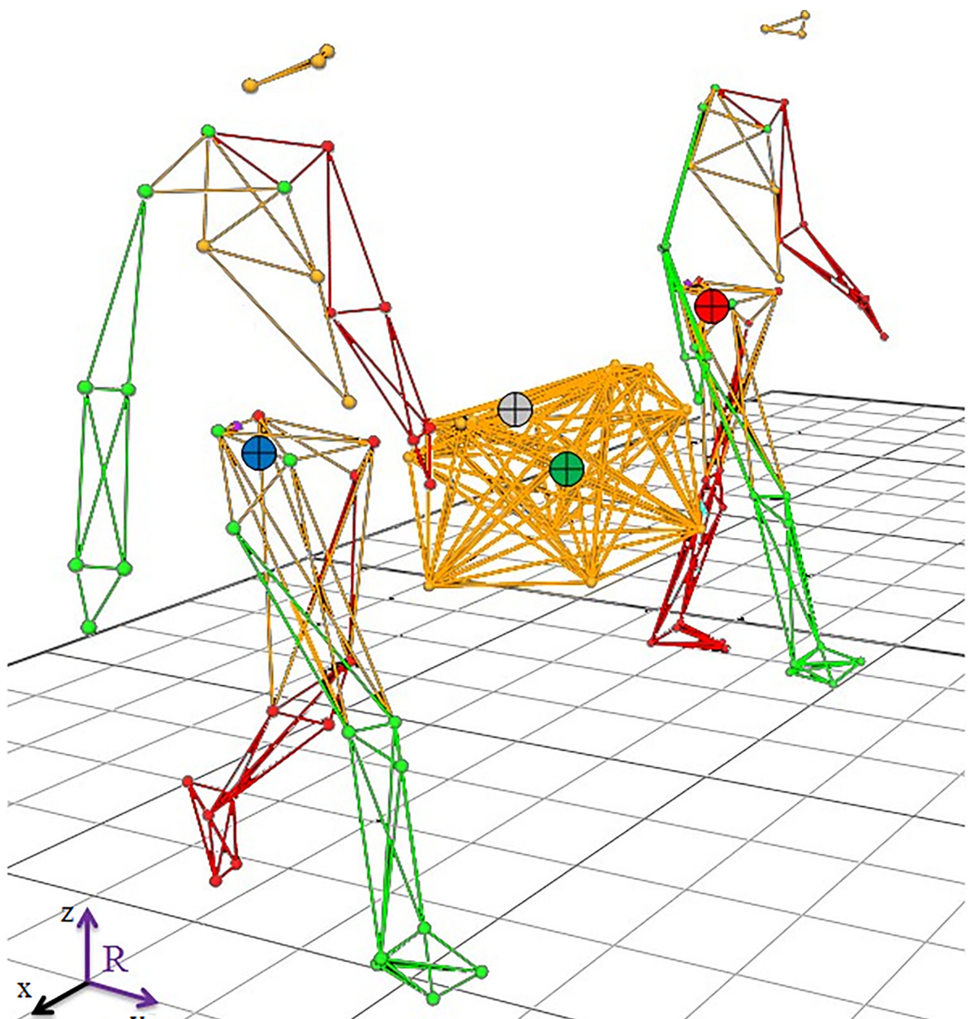

Fig. 1. Reconstruction of the individuals and the box they carry on Vicon Nexus™. The left side of the body is represented in red, the right side in green and the head, trunk and pelvis in orange. The points correspond to the locations of the markers. The circled crosses represent the CoM of individual 1 (red), individual 2 (blue), the box (green) and the PACS (grey). The sagittal plane is in purple in the R referential (external coordinate system), with x the medio-lateral axis, y the antero-posterior axis and z the vertical axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

speed.

2. Material and methods

2.1. Population

Twenty healthy male volunteers tested by pair (mean ± SD: individual 1 on the left side of the load: height = 1.77 ± 0.07 m, mass = 74.78 ± 9.00 kg; individual 2 on the right side of the load: height = 1.77 ± 0.05 m, mass = 74.54 ± 12.38 kg) performed successively three trials at spontaneous speed on a 13m-long walkway (Fig.1). The individuals walked side by side with a box (mass = 13.41 kg) they carried by two lateral handles. The mass of the box was close to 10% of the body-mass of the two individuals. This way we respected a level of activity practiced daily by the individuals, according to the definition of a non-interventional study of the CNRS bioethical office. Informed consent was obtained from all participants.

2.2. Experimentation

Thirteen infrared (11 MX3 and 2 TS40) transmitter-receivers video cameras (Vicon©, Oxford metric's, Oxford, United Kingdom) were used to acquire the kinematic data of one gait cycle by trial. The Vicon calibrated volume (30 m^3) was set in the middle of the walkway to record the walking patterns at stable speed. The gait cycle of the PACS was recorded from the first heel strike of individual 1 to the third heel strike of individual 2. Ninety-eight retro-reflective markers were placed on the PACS (i.e. 42 on each individual according to Wu et al. [9,10] and 14 on the box), and their positions were recorded at a frequency of 200 Hz (filtered with a 4th order Butterworth filter and a 5 Hz cut frequency). The kinematic analysis of the PACS was carried out with the software Vicon Nexus™ 1.8.5 (Fig. 1).

2.3. Computed parameters

The De Leva Anthropometric tables [11] allowed us to estimate the mass m_i and the CoM$_i$ of each segment and to assess the global CoM of the PACS (Fig. 1). The CoM of the PACS (Eq. (1)) was computed as follows:

$$\boldsymbol{G_{PACS}} = \frac{1}{m_{PACS}} \sum_{i=1}^{n=33} m_i \boldsymbol{G}_i \tag{1}$$

With $\boldsymbol{G_{PACS}}$ the 3D position of the PACS CoM in the frame R (the global coordinate system), m_{PACS} the mass of the PACS, n the number of PACS segments (i.e. 16 segments per volunteer plus one segment for the box) and $\boldsymbol{G_i}$ the 3D position of the CoM$_i$ in the frame R (Fig. 1).