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Center of mass trajectory and orientation to ankle and knee in sagittal plane is maintained with forward lean when backpack load changes during treadmill walking

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ABSTRACT

Maintaining the normal shape and amplitude of the vertical trajectory of the center of mass (COM) during stance has been shown to maximize the efficiency of unloaded gait. Kinematic adaptations to load carriage, such as forward lean have yet to be understood in relation to COM movement. The purpose of this study is to better understand how load impacts the vertical COM_{TSYS} trajectory and to clarify the impact of forward lean as it relates to the dynamics of sagittal plane COM_{TSYS} movement during stance with changing load. 17 subjects walked on treadmill at a constant preferred walking velocity while nine different loads ranging from 12.5% to 40% bodyweight were systematically added and removed from a backpack. Kinematic data were collected using an Optotrak, three-dimensional motion analysis system and used to estimate position of the COM as well as segment and COM-to-joint vector orientation angles. The shape and amplitude of the COM vertical trajectory was maintained across all loaded conditions. The orientations of COM-to-ankle and -knee vectors were maintained in all loaded conditions except the heaviest load (40% BW). Results suggest that forward lean changed linearly with changes in load to maintain the COM-to-ankle and -knee vector orientations. COM vertical trajectory was maintained by a combination of invariants including lower-limb segment angles and a constant direction of toe-off impulse vector. The kinematic invariants found suggest a simplified control mechanism by which the system limits degrees of freedom and potentially minimizes torque about lower-extremity joints with added load.

1. Introduction

Without compensatory changes, wearing a loaded backpack results in a posterior and superior relocation of the position of the center of mass of the total system (COM_{TSYS}), in the sagittal plane (Singh and Koh, 2009; Yen et al., 2011). Forward lean of the trunk, neck and head is widely observed during loaded gait (Atwells et al., 2006; Knapik et al., 2004) and is considered a direct response to this relocation of the COM_{TSYS} (Singh and Koh, 2009; Yen et al., 2011). The function of forward lean is often explained as a mechanism to bring the COM_{TSYS} within the base of support and closer to the ground, thus improving balance (Atwells et al., 2006; Polcyn et al., 2001). While this explanation may be sufficient from a static perspective and may apply to the brief periods of double-support and mid-stance, gait is fundamentally an act of controlled falling (Diedrich and Warren, 1998), with the COM_{TSYS} traveling outside the base of support for the majority of the gait cycle (Winter, 1995). The impact of forward lean on the movement of the COM_{TSYS} needs greater clarification.

One possible role for forward lean would be to maintain the COM_{TSYS} in a position such that the vector from the COM_{TSYS} to the ankle in the sagittal plane (COM_{TSYS}-to-ankle) remains constant across load conditions. This may be important because in normal gait the body's center of mass (COM) to ankle vector is a determinant of differences; in the push-off impulse at the ankle that maintains the velocity of COM trajectory (Kuo, 2002), in the body's angular momentum around the COM (Neptune and McGowan, 2011), and in the vertical COM trajectory in walking and running (Lee and Farley, 1998).

Movement of the COM behaves as an inverted pendulum during the stance phase of gait (Lee and Farley, 1998; Holt, 1998). Maintaining the amplitude and sinusoidal shape of the vertical COM trajectory during stance ensures an optimal exchange of kinetic and potential energy and minimizes

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metabolic cost (Massaad et al., 2007; Ortega and Farley, 2005). Adding load to the back without compensatory adjustments in COM_{TSYS} location would lead to differences in the push-off impulse and COM_{TSYS} trajectory and potentially decrease the effectiveness of the inverted pendulum dynamics in conserving energy. A linear increase in forward lean under linearly increasing loads would maintain the COM_{TSYS}-to-ankle vector without changing joint kinematics.

If forward lean maintains the trajectory of the COM_{TSYS} across differing loads without changes in joint kinematics, the line of gravity of the COM_{TSYS} would remain a relatively fixed perpendicular distance (i.e. moment arm) from the ankle and knee axes of rotation in the sagittal plane despite changes in load. Minimizing any increase in this moment arm is particularly important because carrying load has consistently been shown to increase ground reaction forces (Birrell et al., 2007; Tilbury-Davis and Hooper, 1999) and consequently increase torques about lower-extremity joints (Harman et al., 2000). If the line of gravity of the COM_{TSYS} is allowed to remain in a more posterior location relative to joints during the early stance phase, then torque would increase by virtue of both the higher load and an increased distance of the load from the joints axes. An alternative strategy to minimize torque about these joints would be to increase forward lean proportionately to increases in backpack load thereby moving the line of gravity of the COM_{TSYS} more anteriorly and closer to the joint axes in the sagittal plane.

Another primary determinant of vertical COM_{TSYS} trajectory is the degree of compression in the inverted pendulum during stance (Lee and Farley, 1998). Thus, invariance or covariance in lower-extremity segment angles despite changes in backpack load would help to ensure that the COM_{TSYS} trajectory is maintained (Lacquaniti et al. 2002, 2012). Earlier research showed that increases in velocity of walking and load leave lower-extremity kinematics unchanged thereby maintaining constant vertical amplitude of the COM_{TSYS} trajectory (Holt et al., 2003; Tilbury-Davis and Hooper, 1999). In contrast, increases in knee joint angle throughout stance result in a flatter shape or decreased amplitude of the vertical COM trajectory (Ortega and Farley, 2005).

The purpose of this study was to better understand how load impacts the vertical COM_{TSYS} trajectory and to clarify the impact of forward lean as it relates to the dynamics of sagittal plane COM_{TSYS} movement during stance with changing load. Given the potential increase in metabolic cost of changing vertical COM_{TSYS} trajectory (Ortega and Farley, 2005) with added load, we hypothesized that vertical COM_{TSYS} trajectory would be minimally impacted by load. In order to maintain vertical COM_{TSYS} trajectory, we further hypothesized that sagittal plane orientations of the vectors from COM_{TSYS} to the ankle and COM_{TSYS} to the knee, as well as lower-extremity segment angles, would be held constant across loaded conditions. It was further expected that forward lean of the trunk and head–neck system would be linearly altered with increments in load in order to preserve COM_{TSYS}-to-ankle and -knee vector orientations during the stance phase of gait.

2. Methods

17 individuals participated in the study (9 males, 8 females, age 25.4 ± 5.2 years; mass 70.6 ± 11.0 kg; height 1.7 ± 0.7 m). Subjects had no history of cardiopulmonary, neurological impairment, or injury that would limit treadmill walking for longer than 1 h. Subjects participated in strenuous exercise at least 3 days per week. The Institutional Review Board of Boston University approved the study and subjects provided written informed consent.

A unique experimental apparatus was built to continuously manipulate load in small increments (Fig. 1). A backpack frame and attached tank, constructed of aluminum, was secured to the thorax using shoulder straps and a sternum strap. The tank could be gradually filled with and emptied of water. A baffling system within the tank minimized sloshing. Custom software controlled volumes of water being fed into and out of the pack as subjects walked on the treadmill. Appendix 1 contains additional specifications.

The length of subjects' body segments were measured for anthropometric calculations, using anatomical landmarks listed in Table 1. The subjects were then fitted with 20 infrared light emitting diodes on those anatomical landmarks.

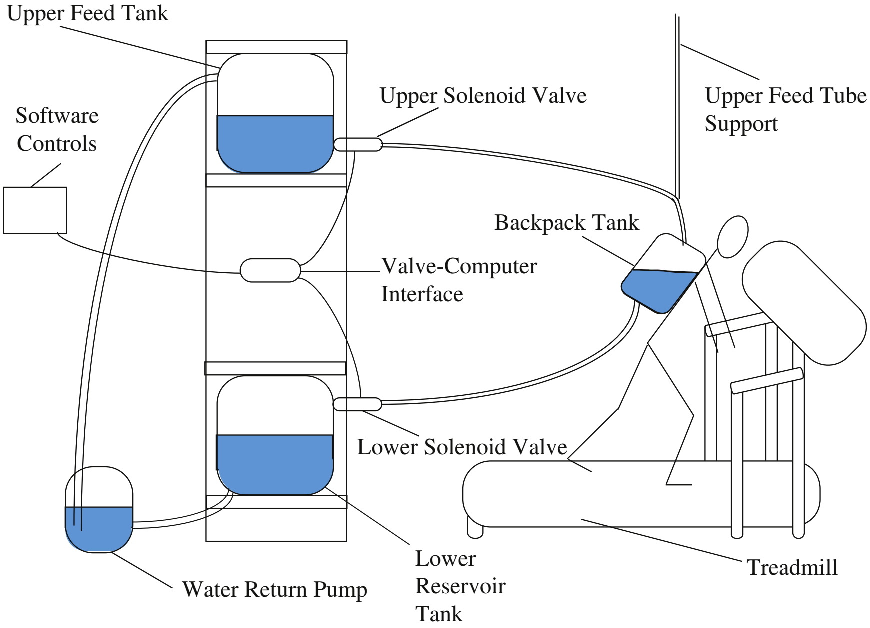

Fig. 1. Subjects carried load using a backpack attached to their rear-upper thorax. The pack consisted of a baffled tank, designed to minimize sloshing. Water was gravity fed from the feed tank into the pack to increase load and then from the pack into the reservoir tank to decrease load. An active pump returned water from the reservoir tank to the feed tank. Water release into and out of the pack tank was controlled with solenoid valves. The valves were controlled and water release data recorded via custom software acting through a custom-built electronic interface. The weight of the empty pack was calculated using a load cell prior to the experiment. The system was then calibrated using the load cell to ensure that the weight within the pack during experimentation could be calculated using the flow rate from the solenoid valves. The software controls specified the release of the necessary water to adjust the total weight of the backpack plus water to the desired percentage of subject's bodyweight. See Appendix 1 for additional specifications.