Towards Exoskeletons with Balance Capacities

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Abstract Current exoskeletons replay pre-programmed trajectories at the actuated joints. Towards the employment of exoskeletons with more flexible and adaptive behavior, we investigate human balance control during gait. We study human balance control by applying brief force pulses at the pelvis in different directions, with different amplitude, and applied at different phases of the gait phase. The observed changes were dependent on the phase at which the perturbation was applied and the walking velocity. From the results we concluded that foot placement was the dominant strategy in the frontal plane, center of pressure (CoP) modulation in the double support phase was utilized in the sagittal plane, and the duration of the swing and double support phase changed. Without the ability to control the CoP through an ankle torque, humans also used a foot placement strategy in the sagittal plane. The center of pressure with respect to the center of mass at the end of the double support phase was linearly related to velocity of the center of mass at the end of the preceding swing phase, which is in agreement with extrapolated center of mass or capture point based stepping strategies previously applied in simple models.

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1 Introduction

Most current exoskeletons are unable to stay upright without assistance and guidance of its user. Paraplegic users, for example, require crutches to prevent falling. In the EU Balance and Symbitron projects we aim to support balance control by wearable exoskeletons. Since human balance control during walking is still poorly understood we performed a series of experiments to analyze balance recovery during gait in attempt to predict human balance control strategies.

2 Materials and Methods

2.1 Experimental Setup and Protocol

Nine healthy young adults walked on a custom dual-belt instrumented treadmill (MotekForce Link, Culemborg, Netherlands), while keeping arms crossed over the abdomen. Walking speeds were 2.25 and 4.50 km/h, scaled to the subject's leg length. For each speed, subjects first walked a 2 min unperturbed baseline trial. In subsequent trials, perturbations were applied to the pelvis using one of two motors (Moog, Nieuw-Vennep, Netherlands), connected with a lever arm to a pelvic brace (Distrac, Hoegaarden, Belgium), worn by the subject. The motors were located at the side and the rear of the treadmill. Our experimental setup is shown in Fig. 1.

Fig. 1 Experimental setup

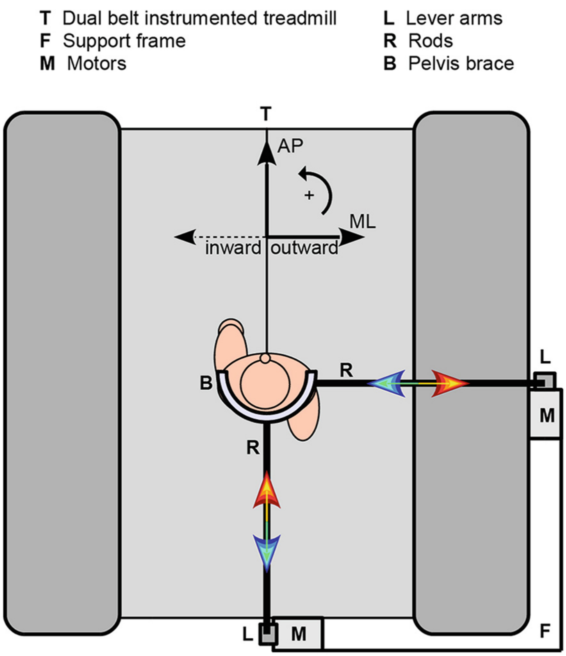

Fig. 2 Pin-foot boots worn by subjects in one of the experiments to study the effect of foot placement in the sagittal plane, to prevent modulation of the cop by changes in ankle torque

Perturbations were applied at randomly selected instances just after toe-off right (TOR), and consisted of 150 ms block pulses of a force magnitude equal to 4, 8, 12 and 16 % of the subject's body weight.

Perturbation directions were forward (positive), backward (negative), outward (positive, away from stance leg) and inward (negative, toward stance leg). Each perturbation type was repeated 8 times, leading to 256 perturbations per subject. Kinematic data of various landmarks on the lower extremities, pelvis, trunk and head [1] were collected at 100 Hz using a motion capture system (Phoenix Technologies Inc, Vancouver, Canada). Ground reaction forces, subject-motor interaction forces, and EMG data were collected at 1000 Hz. More details about the experimental setup can be found in [2]. To exclude the ankle strategy (i.e. modulation of the center of pressure (CoP) by applying an ankle moment), we did a variation of this experiment in which subjects were wearing a pin foot (Fig. 2) while only the backward and forward perturbations were applied at the slow walking speed.

3 Results

At heel strike (HS) after the perturbation, recovery from mediolateral (ML) perturbations involved ML foot placement adjustments proportional to the ML CoM velocity. In contrast, for anterior posterior perturbations (AP) no significant AP foot placement adjustment occurred at HS (Fig. 3 left). However, in both directions the

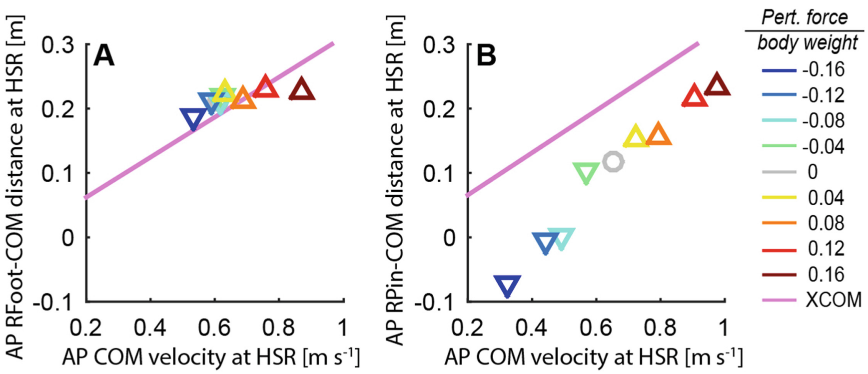

Fig. 3 Typical example of one subject. The foot placement of the right leg (i.e. the AP distance of the right foot with respect to the CoM) at heel strike right (HSR) plotted against the AP CoM velocity at HSR

CoM velocity at HS related linearly to the CoP location at the subsequent toe-off (not shown). This relation was affected by the walking speed and was, for the slow speed (not shown), in line with a CoM velocity based control strategy previously applied by others in a linear inverted pendulum model [3]. Finally, changes in gait phase durations (not shown) suggest that the timing of actions could play an important role during the perturbation recovery. Results of this experiment not shown here can be found in [2]. When subject were wearing the pin-foot boots, recovery from AP perturbations also involved AP foot placement, which were proportional to the AP CoM velocity at HS (Fig. 3 right).

4 Discussion

These experimental results have implications for the control and design of wearable exoskeletons that aim to support human balance control. In AP directions XCoM at HS can be used to predict the desired CoP location at the end of double support phase. For ML directions xCoM can be used to predict the desired foot placement relative to the CoM. For human-like ML stabilization wearable exoskeletons need actuated hip ab/adduction, and for AP stabilization they require torque controlled ankle actuation.

5 Conclusions

The CoP is a main variable humans use to maintain balance during gait. In the ML direction CoP is controlled by foot placement and in the AP direction by ankle torque and foot placement. When ankle torque cannot be used to change the CoP in the AP direction, humans switch to the foot placement adjustment strategy in the sagittal plane. The CoP at the end of the double support phase is linearly related to the CoM velocity at the end of the preceding swing phase. Timing of foot placement is an important variable for balance control, which is more difficult to predict.

References

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