ACTIVE CONTROL OF LATERAL BALANCE IN ANKLE-FOOT COMPLEX SYSTEM

VALERICA MOŞNEGUŢU, MARIUS IONESCU, DAN DUMITRIU, VETURIA CHIROIU

Abstract. The goal of balance is to avoid falls and keeping the body center of mass over the base of the support. The control of the quiet, upright stance consists from a set of simple feedback laws where a deviation from a set point detected by one or multiple sensor signals, is mapped onto a counter force that brings the center of mass to the set point. This counter force is usually assumed to be generated by the ankle musculature. Walking can be characterized as a sequence of controlled falls.

Key words: Active control, ankle-foot system.

1. INTRODUCTION

The solutions for controlling the response of the ankle-foot systems under lateral balance have been moving from passive control to smart and active or semi-active techniques. While passive systems cannot adapt to changes in moving properties, active control can adapt to a wide domain of conditions and properties. But the passive result increases in costs and reliability. Therefore, the semi-active control is able to achieve a compromise between active and passive control by combining the reliability of passive control with the adaptability of the active control.

The modeling of biped robots can be divided into two classes. The first class uses the dynamical parameters to generate the walking. The trajectories of the joint angle [1–4] and the trajectories of feet are generally expressed by spline or polynomial functions where the unknown parameters are determined by a genetic algorithm or other optimization techniques [5–9]. The nonlinear analysis of normal human gait for different activities with application to bipedal locomotion is analyzed in [6], while the experimental measurement of the flexion-extension movement in normal and arthritic human knee is presented in [8].

The second class uses simplified models to describe the generate walking. Inverted pendulum [10, 11] is one of the simplest methods. The robot consists from

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a concentrated mass and massless leg. The center of mass trajectories is generated together with the angles of the joints by inverse kinematics. A simple linear inverted pendulum model with analytical solutions is described in [11, 12]. Another model is the inverted pendulum model with constant leg length and the center of mass with trajectories as arcs [13–15]. Due to its nonlinearity, the problem has no analytical solutions.

We discuss in this paper different motor actions available to the center of mass to achieve the avoiding the falls. The center of mass movement can be corrected in a goal-directed way. The walking body can be modeled as a point mass on a massless leg with a single ground contact point.

The movement of that point in the horizontal plane is entirely defined by the velocity of the center of mass and its distance from the ground contact point, or center of pressure. The relationship between these two points is that the horizontal acceleration of the center of mass is proportional to the displacement between the center of mass and the center of pressure. We limit our study to the medial-lateral direction here, but the anterior-posterior direction is analogous.

Consider that the center of mass moves along a straight line, which is horizontal. In this case, the resultant force in the vertical direction is zero. The differential equation that describes the motion of the center of mass are

$$\ddot{x} = \frac{g}{z_0} x, \tag{1}$$

where z_0 is a constant and (x, z_0) is the position of the center of mass. The solution of (1) is written as

$$\begin{aligned} x(t) &= A\exp(t/T_0) + B\exp(-t/T_0), \\ \dot{x}(t) &= A'\exp(t/T_0) + B'\exp(-t/T_0), \end{aligned} \tag{2}$$

with

$$\begin{aligned} A &= \frac{x(0) + T_0\dot{x}(0)}{2}, \ B = \frac{x(0) - T_0\dot{x}(0)}{2}, \\ A' &= \frac{x(0) + T_0\dot{x}(0)}{2T_0}, \ B = \frac{x(0) - T_0\dot{x}(0)}{2T_0}, \end{aligned} \tag{3}$$

where $x(0)$ and $\dot{x}(0)$ define the initial values, and T_0 is a constant given by $T_0 = \sqrt{\frac{z_0}{g}}$. The three positions for walking with the acting ankles are shown in Fig. 1.

The phases of the human motion are shown in Fig. 2 for the initial-impact phase and the resting phase, respectively.

Fig. 1 – Three positions of the human motion.

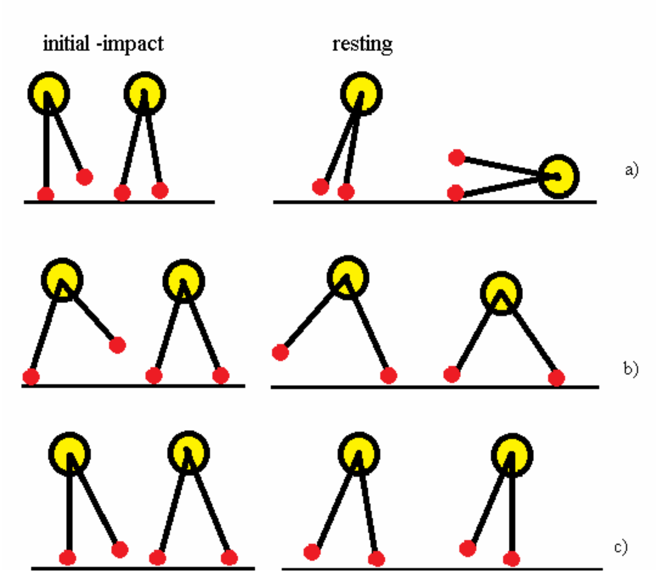

Fig. 2 – Human locomotion phases.

2. BIPED LINEAR INVERTED PENDULUM

The scheme of the inverted pendulum is presented in Fig. 3. By multiplying (1) with $\dot{x}$ and after integration we obtain the conservation law

$$\frac{1}{2}\dot{x}^2 - \frac{g}{2z_0}x^2 = \text{const.}, \tag{4}$$

where the constant expresses the orbital energy of the model. From (3), the time transfer of moving from a point to another point on a moving straight line, is obtained as

$$\tau_0 = T_0 \frac{x_1 + T_0\dot{x}_1}{x_0 + T_0\dot{x}_0} \text{ or } \tau_0 = T_0 \frac{x_1 - T_0\dot{x}_1}{x_0 - T_0\dot{x}_0}. \tag{5}$$

If k_0 is the slope of the line when center of mass moves under a force f, and z_0 is the intersection of the z-axis with the line, the oblique trajectory is written as $z = k_0 x + z_0$. The motion equation is independent of the slope of the line and it is given by $\ddot{x} = \frac{g}{z_0} x$, which has the same form with (1) in the x-direction. That means that if the initial conditions $x(0)$ and $\dot{x}(0)$ are the same, three kinds of motions are obtained for pendulum. These motions are shown in Fig. 4. The force f is acting on the pendulum of mass M.

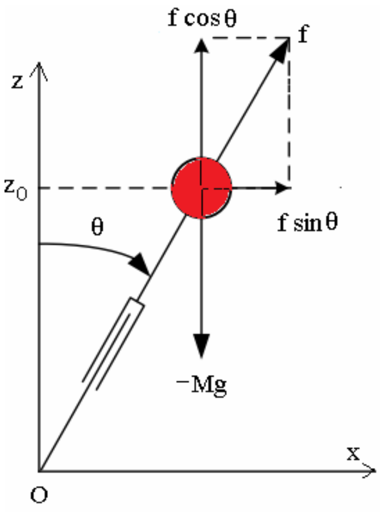

Fig. 3 – Linear inverted pendulum.

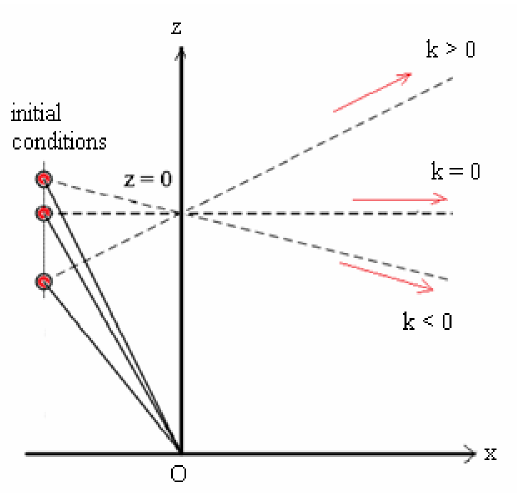

Fig. 4 – Three types of the pendulum motion.

The velocity of the center of mass during the walking in the x-direction for $z_0 = 0.9$ m, with the step length $L = 0.4$ m is 0.3 m/s^2. Consider that the time duration of walking for a trajectory $k > 0$ is 0.77 s, and the trajectory for $k < 0$ is 0.16 s. The average speed of periodic walking is 0.43 m/s.

The center of mass velocity in the x-direction for periodic walking is presented in Fig. 5. Figure 6 shows the velocity of the center of mass for walking with fixed step length. The blue line represents the single support step and the red line the double support line. The positions of the center mass in the x-direction and respectively, in the x-direction is displayed in Figs. 7 and 8.

We note by (x,z) the contact point position of the contact point, and $\Delta x = x - x_g$, $\Delta z = z - z_g$ with (x_g, z_g) the initial position of the contact point, k_x, c_x, the stiffness and damper coefficients in the tangential direction, k_z, c_z , the stiffness and damper coefficients in the normal direction, and ρ and ζ the influence coefficients of the penetration depth to k_x, c_x. So, the contact force can be expressed as

$$f_x = -k_x \Delta x \,|\, \Delta z \,|^{\rho} - c_x \Delta \dot{x} \,|\, \Delta z \,|^{\varsigma}, \tag{6}$$

$$f_z = \begin{cases} k_z \,|\, \Delta z \,|^{\rho}, & \Delta z \le 0, \quad \Delta \dot{z} \ge 0, \\ k_z \,|\, \Delta z \,|^{\rho} + c_z \Delta \dot{z} \,|\, \Delta z \,|^{\varsigma}, & \Delta z \le 0, \quad \Delta \dot{z} \le 0, \\ 0, & \Delta z > 0. \end{cases} \tag{7}$$

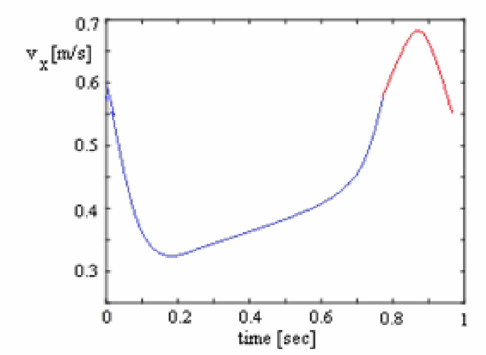

Fig. 5 – Velocity of the center of mass in x-direction for periodic motion.

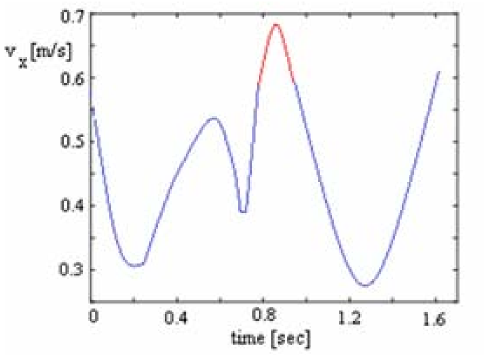

Fig. 6 – Velocity of the center of mass for walking with fixed step-length equal to 0.3 m.

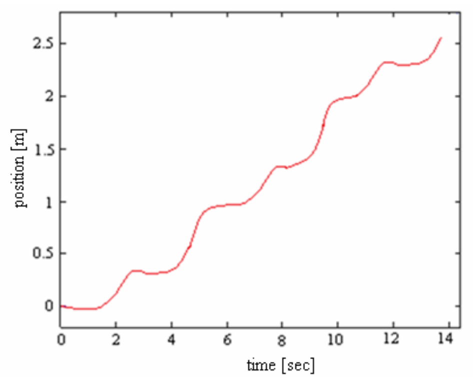

Fig. 7 – Position of the center of mass in the x-direction.

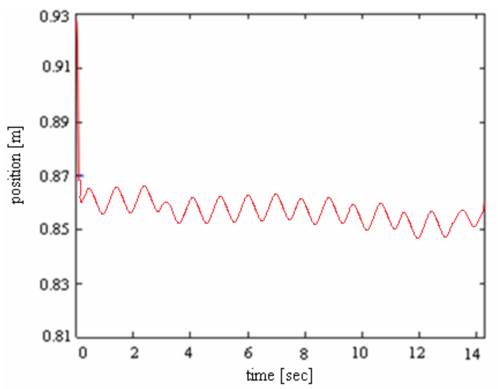

Fig. 8 – Position of the center of mass in the z-direction.

3. ACTIVE CONTROL OF BALANCE IN ANKLE-FOOT COMPLEX SYSTEM

We suppose that the ankle-foot system has a full contact with the ground. The controller with a simple impedance is defined as in [16] and characterized by the equations:

$$\begin{aligned}
\tau_{1,\mathrm{PF}} &= K_{PF}(\theta_0-\theta_1)-B_{PF}\omega_1,\\
\tau_{1,\mathrm{DF}} &= K_{DF}(\theta_0-\theta_1)-B_{DF}\omega_1,\\
\tau_{1,\mathrm{PP}} &= K_{PP}(\theta_0-\theta_1)-B_{PP}\omega_1+\Delta\tau_{PP},\\
\tau_{1,\mathrm{SW}_2} &= K_{SW}(\theta_0-\theta_1)-B_{SW}\omega_1,
\end{aligned} \tag{8}$$

where PF means the plantar ankle flexion, DF means the dorsal flexion which describes the bending flexion in the dorsal direction, PP denotes the power plantar flexion, and SW, SW2 denote two swing phases which describe the initial swing and terminal swing.

The ankle-foot trajectory is given as the average of five gait cycles of $M = 70$ kg, captured using Vicon system for $k_x = 4.1\times 104$, $c_x = 8.8\times 105$, $k_z = 9.0\times 104$ (Fig. 9), [9]. The gait signature of the walking motion are: a) $\theta-u$ without control and b) $\theta-u'$ with control. Figure 10 presents the active posture control. The gait signature of the walking motion without control and with control is presented in Fig. 11. The gait signature is defined as a sequence of figures obtained from one gait cycle.

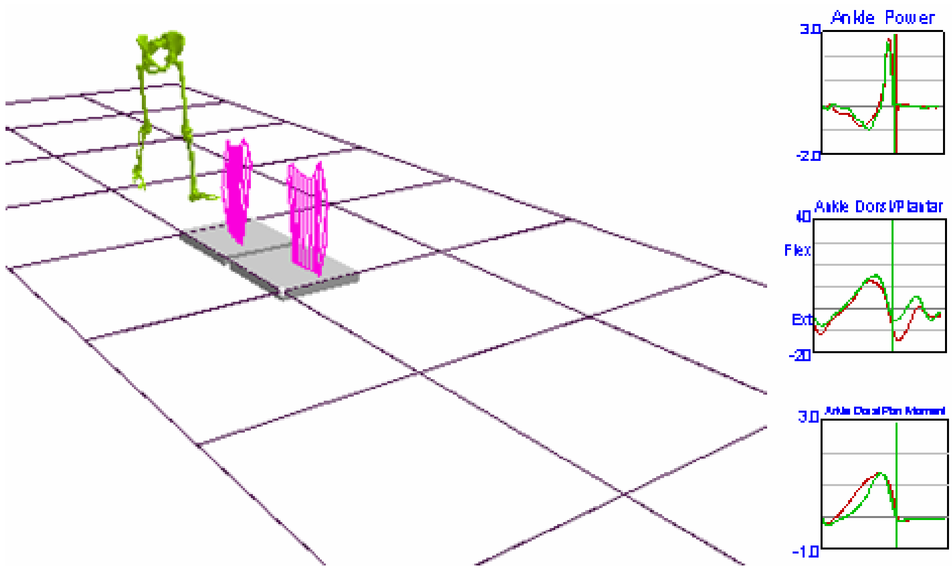

Fig. 9 – The ankle-foot trajectory captured using the Vicon system [17, 18].

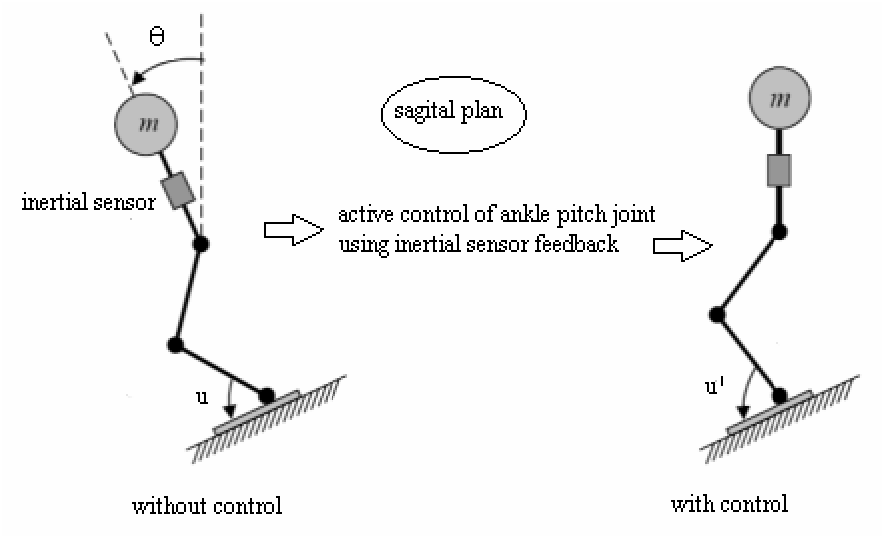

Fig. 10 – Active posture control.

The ankle-joint system provides an evaluation strategy for understanding different injury mechanisms based on the functionality of the joints and muscles throughout the ankle complex. Accurate evaluation of the gait signature for walking motion without/and control relies on correctly identifying all involved structures in the ankle-joint system.

The difference between the two gait signatures (without and with control) is important and helps the gait to prevent, diagnose and rehabilitate the loss of stability and independence due to deficiencies that may arise on the gait.

The gait analysis can support the therapists' decisions on the abnormalities and changes due to orthopaedic interventions.

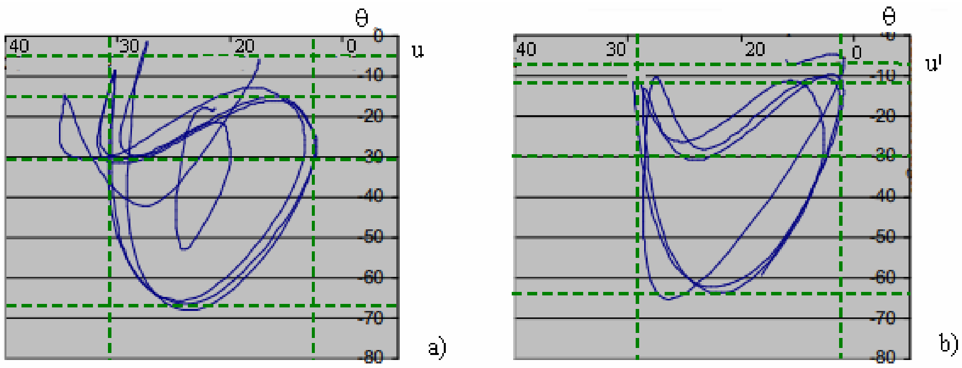

Fig. 11 – Gait signature of the walking motion: a) without control; b) with control.

4. CONCLUSIONS

In this research, we presented an analysis of the walking balance of keeping the body center of mass over the base of the support. The force absorption and propulsion in the ankle complex motion are necessary for any activity in weight bearing. Walking is characterized as a sequence of controlled falls with emphases to the ankle instability and the lateral ankle sprains. The gait can be seen as an oscillating model of the force accommodation in the walking process. Throughout the gait cycle, a cyclical absorption and the propulsion occurs. The absorption decelerates and controls the progression, and the propulsion continues the progression. Many musculoskeletal injuries occur because of improper force absorption in a poor mechanics where the bad landing or the stumble on slippery surfaces occurs.

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