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All leg joints contribute to quiet human stance: A mechanical analysis

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ABSTRACT

According to the state of the art model (single inverted pendulum) the regulation of quiet human stance seems to be dominated by ankle joint actions. Recent findings substantiated both in-phase and anti-phase fluctuations of ankle and hip joint kinematics can be identified in quiet human stance. Thus, we explored in an experimental study to what extent all three leg joints actually contribute to the balancing problem of quiet human stance. We also aimed at distinguishing kinematic from torque contributions. Thereto, we directly measured ankle, knee, and hip joint kinematics with high spatial resolution and ground reaction forces. Then, we calculated the six respective joint torques and, additionally, the centre of mass kinematics. We searched for high cross-correlations between all these mechanical variables. Beyond confirming correlated anti-phase kinematics of ankle and hip, the main results are: (i) ankle and knee joint fluctuate tightly (torque) coupled and (ii) the bi-articular muscles of the leg are well suited to fulfil the requirements of fluctuations around static equilibrium. Additionally, we (iii) identified high-frequency oscillations of the shank between about 4 and 8 Hz and (iv) discriminated potentially passive and active joint torque contributions. These results demonstrate that all leg joints contribute actively and concertedly to quiet human stance, even in the undisturbed case. Moreover, they substantiate the single inverted pendulum paradigm to be an invalid model for quiet human stance.

1. Introduction

Quiet human stance is a tricky motor task that has drawn the focus of interest for at least four decades (Murray et al., 1967; Gurfinkel and Osevets, 1972; Geursen et al., 1976). Tracing the solution of this task solely back to a sum of ankle torques that counter-acts in proportion to a horizontal COM displacement is the most obvious approach. The respective model is the single inverted pendulum (SIP) still being the paradigm within recent studies (Winter et al., 2003; Mergner et al., 2003; Gage et al., 2004; Kiemel et al., 2006; Madigan et al., 2006; Masani et al., 2006, 2008; Bottaro et al., 2008). To stabilise the SIP model the stiffness of the respective rotational single degree of freedom (DOF) would have to be over-critical (Fitzpatrick et al., 1992; Winter et al., 1998; Morasso and Schieppati, 1999). If in reality the only DOF deflected was the lumped ankle angle, the stiffness of all muscles actuating the ankles and the predicted over-critical stiffness would match.

There are indications that focussing on the ankle, applying either stiffness or other actuating concepts (Loram and Lakie, 2002; Loram et al., 2005), may be misleading referring to the biomechanical nature of quiet human stance. First, experiments have already showed that the ankle angle is not the only DOF deflected during quiet human stance, but also knee and hip joint angles fluctuate continuously (Day et al., 1993; Hsu et al., 2007; Günther et al., 2009). Second, earlier experiments indicated (Nashner and McCollum, 1985; Horak and Nashner, 1986) that both an "ankle strategy" and a "hip strategy" may contribute to re-stabilisation of disturbed human stance. Recent findings (Wilson et al., 2006) prove that also the knee joint plays an active role in counter-acting disturbances.

Experimental findings point to the SIP being an over-simplified model (Günther et al., 2009) also for quiet human stance. In contrast, multi-joint coordination seems to come to the fore (Kuo, 2005; Creath et al., 2005; Hsu et al., 2007; Saffer et al., 2008; Günther et al., 2009). One experimental study (Saffer et al., 2008) diagnosed multi-joint coordination through muscle activities, while others (Creath et al., 2005; Hsu et al., 2007) succeeded in separating kinematic in-phase from anti-phase relations of ankle and hip joint along the frequency axis.

An inherently unstable mechanical system as the upright human body could only profit from being designed self-stably (Blickhan et al., 2003, 2007; Grimmer et al., 2008) if it was permanently equipped with uncontrolled, over-critical stiffnesses in all joints (Edwards, 2007). Yet, it is very unlikely that

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Nomenclature

t	time (discrete: index n)
signal	a sequence of values of a measured variable (positional or force component) sampled discretely versus time t
trial	acquisition of one (consistent and synchronised) data set containing the signals of all measured variables
N	number of trials (60)
L	number of data points per trial (512)
SD	standard deviation
min	minimum
max	maximum
$C_{X,Y}$	cross-correlation coefficient between variables X and Y
$\Delta t_{X,Y}$	time lag of maximum $\lvert C_{X,Y}\rvert$ value for one trial
$N_{C_{X,Y}}$	number of trials fulfilling $\lvert C_{X,Y}\rvert \geq 0.8$ and $\lvert \Delta t_{X,Y}\rvert \leq 125\,\mathrm{ms}$
DOF	degree of freedom
SIP	single inverted pendulum
DIP	double inverted pendulum
TIP	triple inverted pendulum
segment	a fraction of whole body mass located between joints (right or left foot, shank, thigh and the HAT)
HAT	segment including head, arms, and trunk
COM	centre of mass
HAT-COM	COM of the HAT-segment

this demand can be fulfilled by the human muscular apparatus for all joints (van Soest et al., 2003; Rozendaal and van Soest, 2005; van Soest and Rozendaal, 2008; Günther et al., 2009). Consequently, in quiet human stance, to counteract gravity, the term 'coordination' inevitably requires active control of the mechanical DOFs by applying constantly fluctuating muscle forces, respectively, joint torques.

In the present study we, therefore, verified whether and to what extent mechanical DOFs other than the ankle joint (knee and hip) may contribute to fluctuations during quiet human stance. Answering this question also implies a verification of the traditional SIP paradigm. We searched for high linear correlations between mechanical variables, including COM and local joint measures. Cross-correlation (Kerr et al., 2008; Akram et al., 2008) or related covariance (Kuo et al., 1998; Kuo, 2005) analysis has already been applied to human stance. Our identified cross-correlations are then interpreted based on mechanical mechanisms due to the anatomical arrangement of some muscles.

2. Methods

2.1. Subjects

Within this study we examined 10 healthy subjects (three female, seven male: 29.7 ± 1.3 yrs, 81.3 ± 9.7 kg, 1.81 ± 0.07 m). Nine of them do recreational activities and one had formerly been an active sportsmen. The experimental procedures were in accordance with the guidelines of the University of Tübingen Ethics Committee. Prior to the study, all subjects gave informed consent to the experimental procedure.

2.2. Experimental setup

The experimental setup consisted of two force platforms ("Kistler" 9281B11, Winterthur, Switzerland) parallelly fixed on ground level and six high-speed video cameras ("VDS Vosskühler" HCC1000, Erlangen, Germany). Three cameras were arranged to the right of the subject's body, and three to the left. Each camera focused on just one joint marker to acquire its motion in the sagittal plane. To benefit from a maximised spatial resolution (see Section 2.4) the maximum camera resolution of 1024×1024 pixel per frame was used. In combination with a sample frequency of 115.5 Hz and a local RAM of 512 MB (512 grey 8 bit images) the cameras were able to store kinematic data for 4.4 s. Therefore, trials were restricted to this period while force platform data were sampled at 1250 Hz. The cameras were triggered by a start signal from the "Kistler" control software "Bioware". A general time offset of one camera sample between cameras and force platform data was found and corrected systematically during data post-processing to prevent potentially serious quantitative errors in inverse dynamics (Günther et al., 2005).

Six markers were attached directly to the subjects' skin, laterally to the hips (trochanter major), knees (1.5 cm above and frontally to most protruding point of the joint gap), and ankles (malleolus). Each marker consisted of a 5×5 cm rectangle of white tape painted with a filled black circle of 3 cm diameter. Segment and joint angle kinematics were calculated from marker coordinates according to Fig. 1.

2.3. Experimental protocol

The subjects were instructed to step on the active force platforms and stand with each foot exclusively on one platform, the feet frontally aligned. A trial was started after they had been given another 5–10 s to find a comfortable position with a stance width of their own choice, while looking constantly at the lab wall 3 m ahead. The extended arms had to be crossed and leant against the frontal pelvis. The resting phases in-between the trials lasted

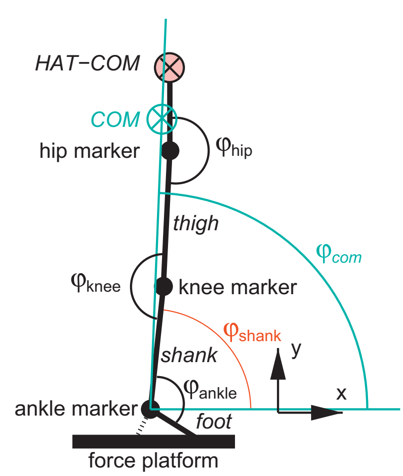

Fig. 1. Marker positions, joint angle definitions, segments, COM, HAT-COM, and the COM angle. The markers are symbolised by black, filled circles. The joint angles φ_{ankle}, φ_{knee}, and φ_{hip} are inner angles, the COM angle φ_{com} and the shank segment angle φ_{shank} are measured with respect to the horizontal in the inertial coordinate system. The other two segment angles φ_{thigh}, φ_{hat} are measured just alike but not depicted here. During quiet stance the fluctuations of the shank (φ_{shank}) and ankle (φ_{ankle}) angle are practically identical as in this study the ankle (marker) positions generally fluctuate just on the border of kinematic spatial resolution. The joint torques are calculated consistently to the respective angle definitions, i.e. without an appropriate positive torque an inner angle would start to flex in the static case.