Control Goals of Whole-Body Coordination During Quiet Upright Stance

Hongbo Zhang(✉)

Department of Engineering Technology, Middle Tennessee State University Murfreesboro,
Murfreesboro, TN 37132, USA
hbzhang@mtsu.edu

Abstract. Whole body coordination is essential for maintaining human posture stability. Yet the control goals and influences of individual differences and task-related effects have not been well investigated. Uncontrolled manifold method was used to assess whole-body coordination during upright stance with 16 young and 16 older individuals. These ratios were obtained for the head, shoulder, and whole-body center-of-mass, in both the mediolateral and anteroposterior directions. As evidenced by larger uncontrolled manifold ratios, the head and shoulder appeared to be more likely than whole-body center-of-mass as control goals for whole body coordination. The present results demonstrate that investigation of head and shoulder kinematics among upright stance posture could be likely yielding clinical meaningful results.

Keywords: Quiet upright stance · Whole body coordination · Uncontrolled manifold · Fall prevention

1 Introduction

Exploration of human postural control is quite crucial for human fall prevention. It is known that human falls are predominant leading to significant injuries and even death. On average, one in three elderly adults older than 65 years age fall annually. Falls lead to bone fracture, muscle injuries, and even death. Fall prevention is a tricky topic and hard to study. It is largely because of the intrinsic challenges of the research topic, research on fall prevention has been very slow. Especially, practical engineering intervention is either not quite useful or cumbersome to implement.

Previous research of falls have mostly focused on the study of human postural controller. Such controller can be PID controller, optimal controller, and intermittent controller [1, 7, 10, 14]. Such postural controllers are mostly inspired from the engineering design. It works well to model a biomechanical system but not necessarily is able to capture the neural muscular structure details. As such, it is desirable to view the postural control system with a new angle. Such new angle starts from the analysis of human postural control from a fundamental level.

Upright stance is inherently unstable due to gravitational torque and internal disturbances such as hemodynamic and neuromuscular noise [1–3]. Previous studies have

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demonstrated that multiple joints contribute to balance control during quiet upright stance [4–14]. Several possible motor control goals have also been suggested, such as maintaining the projection of the center-of-mass (COM) [7, 15, 16] or the center-of-pressure [17] within the base of support and maintaining head and gaze stability [18–20]. Although this earlier work offers some clues as to how whole-body coordination is achieved, as yet there is no consensus. Such divergence provided one motivation for the current study, the aim of which was to explore the potential control goal used for whole-body coordination. Joint coordination is also known dependent on intrinsic aspects of the musculoskeletal system, which differ with age and gender [21–23]. As such, differences related to age and gender were also explored.

To explore potential control goals, kinematics of the head, shoulder, and whole-body COM were examined here. While the shoulder has not been explicitly regarded earlier as a control goal for whole body coordination, a strong biomechanical constraint exists between the head and trunk/shoulder, and these two segments have also been shown to move in a coordinated fashion [20, 24, 25]. Additionally, small relative movements between the shoulder and trunk imply that the shoulder could play an important role for ankle-trunk-shoulder coordination, which is essential for maintenance of quiet upright stance control [7, 26].

The uncontrolled manifold (UCM) ratio has been used for assessing whole-body coordination [27–30]. This approach assumes that control goals achieve minimum variation through coordination involving multiple limb segments [7, 9, 31, 32], and conceptually is similar to coherence analysis used to analyze signal similarities. Through comparison of UCM ratio magnitudes, it is possible to identify the most likely control goals [7, 29]. The UCM ratio method was thus used here for assessing control goals.

2 Methods

2.1 Experimental Data

A subset of data from an earlier experiment [33] were used herein. A total of 32 participants (gender balanced) were involved, half of whom were young adults (18–25 years) and half older adults (55–65) years. Repeated trials of quiet upright stance were measured involving participants standing without shoes, as still as possible, with their feet together, arms by their sides, head upright, and eyes closed. Each trial lasted 75 s, with at least one minute between two consecutive trials. Whole-body kinematics was estimated from surface markers that were tracked using a 6-camera system (Vicon 460, Lake Forest, CA, USA) at 20 Hz [5, 34]. Raw kinematics signals were low-pass filtered (Butterworth, 8 Hz cut-off frequency, 4th order, zero lag, bi-directional) and transformed to obtain body position time series; the first 10 s and the last 5 s of data in each trial were removed to eliminate any potential transition effects.

2.2 Kinematics and Uncontrolled Manifold

Following filtering and windowing of marker data, 3D marker locations were available. The 3D marker is used for calculation of the joint angle. In total, the following angles are calculated. It includes head angle, upper arm angle, lower arm angle, trunk angle, knee angle, ankle angle, and foot angle. For each joint, the distal d1(x, y, z) and proximal positions d2(x, y, z) of the respective body segment were used, along with the equations below, to estimate angles in both the sagittal and frontal planes.

$$\theta_{FPA} = \tan 2^{-1}\left(\frac{d1[z] - d2[z]}{d1[x] - d2[x]}\right) \tag{1}$$

$$\theta_{SPA} = \tan 2^{-1}\left(\frac{d1[z] - d2[z]}{d1[y] - d2[y]}\right) \tag{2}$$

All these angles are calculated in both ML and AP planes. The computed angles are shown in Fig. 1.

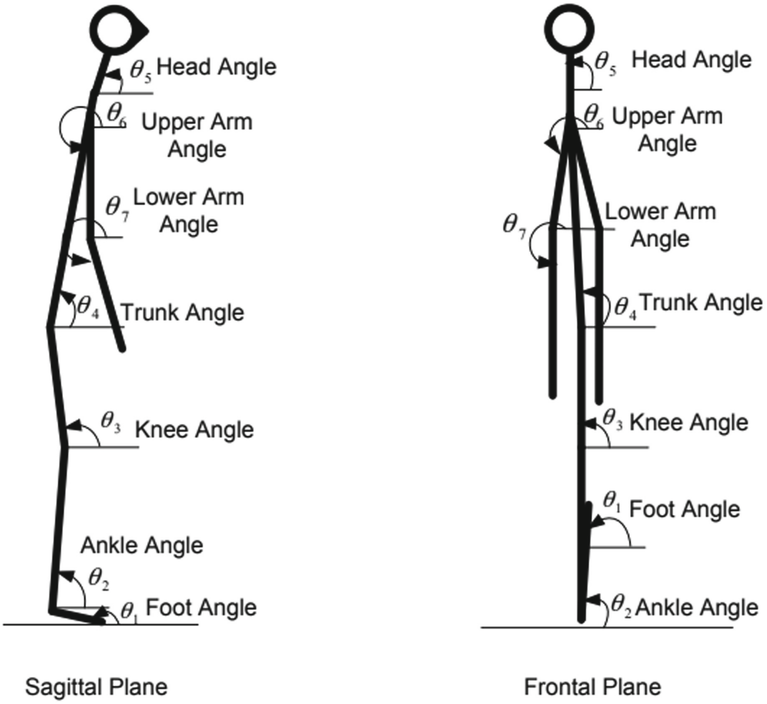

Fig. 1. Kinematics system of the whole body joint angles during quite upright stance

From these, sagittal plane and frontal plane joint segment angles were derived, along with the whole-body center-of-mass (COM) locations, using approaches similar to earlier reports [5, 35]. Major joint angles including neck and trunk segmental joint angles and bilateral means of foot, ankle, knee, shoulder, and elbow segmental joint angles served as input for UCM analysis, along with the noted task variables (locations of the head, shoulder, and COM) [35]. For both the ML and AP directions, time series of these locations were computed using segmental models including the foot, lower leg, upper leg, trunk, head, upper arm, and lower arm, e.g., shoulder position is a summation of projected length of the foot, lower leg, upper leg, and trunk segments. Jacobian matrices were calculated using joint angle derivatives separately for each of these body location, and the null spaces of these were obtained [35].

Projections of variance on the UCM ($UCM_{||}$) and orthogonal to the UCM ($UCM_{\perp}$) were determined as described by [35] with equations as Eq. (3) and Eq. (4),

$$UCM_{||} = \sqrt{[(n-d) \times N]^{-1} \sum\nolimits_{i=1}^{N} \left(\sum\nolimits_{j=1}^{n-d} e_j^T \theta e_j \right)^2} \tag{3}$$

$$UCM_{\perp} = \sqrt{(d \times N)^{-1} \sum\nolimits_{i=1}^{N} \left[\left(\theta - \overline{\theta} \right) - \left(\sum\nolimits_{j=1}^{n-d} e_j^T \theta e_j \right) \right]^2} \tag{4}$$

where N is trial length, n is 6 for COM, 4 for head, and 3 for trunk, d = 1, e_j and e_j^T are the null spaces of Jacobian matrices and the transpose of null spaces of Jacobian matrices. θ is segmental joint angle, and the $\overline{\theta}$ is average of the segmental joint angle.

UCM ratios were finally obtained as: $UCM_{||}/UCM_{\perp}$ [35]. UCM ratios were estimated for each body location, separately in both the AP and ML directions.

2.3 Statistical Analysis

Means of the dependent variable (UCM ratios) were obtained from three trials, and these means were used subsequently in statistical analyses. UCM ratios for the head, shoulder, and COM were compared separately in the ML and AP directions, using paired *t* tests corrected for multiple comparisons. Differences related to age and gender were assessed using separate two-way ANOVAs for each UCM ratio and direction. The level of significance for all tests was set at $p < 0.05$, and all statistical analyses were performed using JMP 9.02 (SAS Inc., Cary, NC, USA). Summary statistics are presented as means (SD).

3 Results

In both the AP and ML directions, all paired differences between UCM ratios of the head, shoulder, and COM were significantly different. These ratios were largest for the shoulder and smallest for the COM. Age x gender interaction effects were significant for several measures, and approached significance otherwise (Table 1 and Fig. 2). Older individuals had higher UCM ratios for Head_{AP} and COM_{AP}, though this age-related difference was more substantial among females. For other measures, the interactive effects were more complex and less consistent.

Table 1. Summary of the effects of Age (A) and Gender (G) on UCM ratios in the antero-posterior (AP) and medio-lateral (ML) directions. Significant effects are bolded (i.e., p values < 0.05). The final column provides the mean (SD) of the UCM ratios across subjects.

		A	G	A x G	UCM ratio
AP	Head	**0.026**	0.44	**0.029**	0.82 (0.00078)
	Shoulder	0.39	0.35	**0.018**	1.34 (0.15)
	COM	**0.0175**	0.59	**0.021**	0.64 (0.0014)
ML	Head	0.60	0.17	0.083	0.84 (0.013)
	Shoulder	0.22	0.14	0.067	1.02 (0.0035)
	COM	0.57	0.95	**0.012**	0.048)

4 Discussion

We investigated whole-body coordination and moderating influences of age and gender during upright stance using the UCM ratio approach. Overall, the current results suggest the importance of the head and shoulder as control goals in quiet upright stance (i.e., larger UCM ratios than COM). The study results have profound applications for postural classification [42].

Regarding the control goal, UCM ratios for the shoulder were > 1 in the AP and ML directions. In contrast, UCM ratios for the COM and head were < 1 in both directions. If the UCM ratio is < 1 for a task variable, task variability is structured in such a way as to not minimize end-effector variability. Therefore, our results suggest that whole body COM is less likely to be a principal control variable during upright stance, supporting previous evidence of that alternative control goal (e.g. head or trunk) are used for whole body coordination [36, 37]. Instead, our results suggest that the shoulder may be more likely to be relevant control variables in both the sagittal and frontal planes. This result might stem from the arm and hand, which contribute to the center of mass position, having low coherence with trunk and leg motions in quiet upright stance (where the arm and hand remain relatively static), leading in turn to less coherent whole-body motion and thus a decreased COM UCM ratio. In contrast, the upper body and leg, which are involved in manipulating the shoulder and head positions, have more substantial coherent motions [6, 32, 38].

Older adults had larger initial UCM ratios in some cases. Though differences were of small magnitude, this may suggest a higher level of goal oriented postural coordination among older adults, perhaps as compensation of postural instability due to larger time delays in the control loop [39–41]. However, there were significant but inconsistent age x gender interaction effects (Fig. 1); further study is needed to better understand these.

The current study has practical research and clinical insights for human postural control and fall prevention. For a long time, it is highly suggested the control of human postural control is centered by the center of mass of human body. While center of mass might be important, according to our study, center of mass is unlikely the human coordination goal. In contrast, shoulder is more likely the whole body coordination goal.

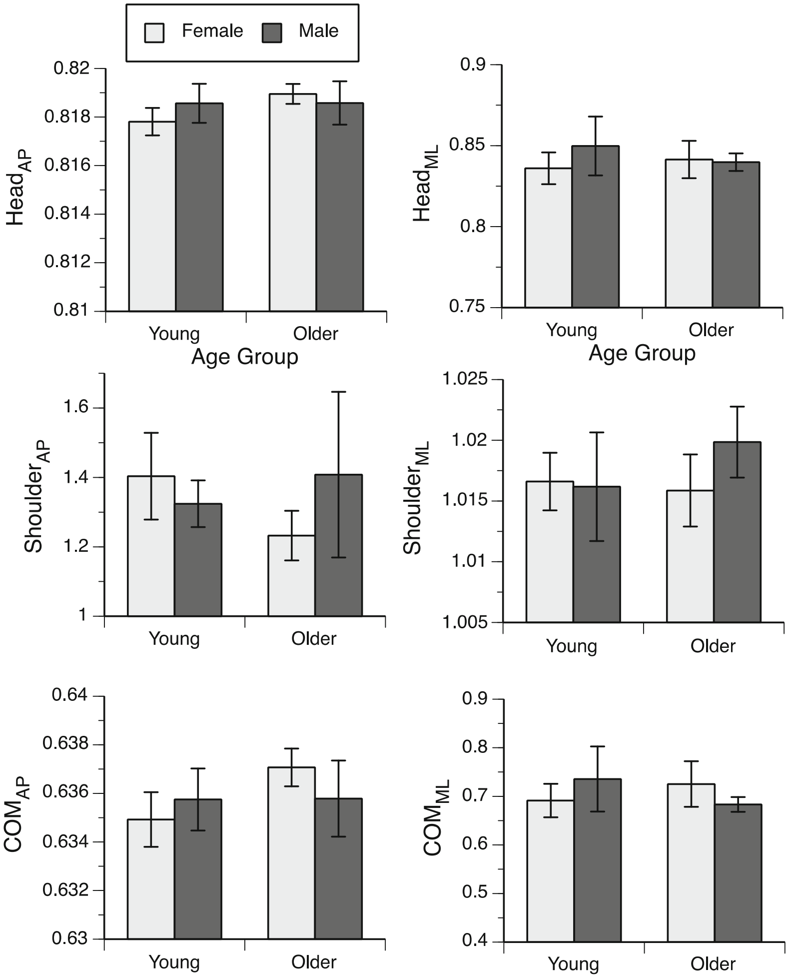

Fig. 2. Effects of age and gender on UCM ratios for the Head, Shoulder, and COM, in both the antero-posterior (AP) and medio-lateral (ML) directions.

As far as the rational behind of it, it is likely driven by the need of maintaining head stability which is a crucial task for human safety. Clinically, our study has important indications. It shows the importance of upper body coordination for fall prevention, which is largely ignored in the past. Hence, the lower and upper body coordination intervention such as Taichi could be likely useful for fall prevention.

The current study is potentially limited in that the UCM method was used in the time domain, though future analysis in the frequency domain may yield additional information. Further investigation of these limitations could help to improve our understanding of whole-body coordination.

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