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Uncontrolled Manifold Analysis of Standing-up Motion for Development of an Assistance System

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***Abstract*—Standing-up motion is essential to performance of the activities of daily life (ADL). In this research, we analyse human standing-up motion in terms of how joint angles coordinate to contribute to the motion. Uncontrolled manifold (UCM) analysis is applied, and degrees of joint coordination are calculated for the entire course of the motion. Those values are investigated for the four phases of the motion to understand which positions of the body are under explicit control. Results indicate that individuals control their hip and shoulder positions in the horizontal direction until extending their upper body and also after they finish lifting up their body. On the other hand, it is shown that vertical direction of the hip and shoulder are controlled until the time they bend their back and lift up their hip. Based on time series of calculated joint coordination over the entire standing-up motion, we suggest a new control method for our previously developed force assisting system. The controller allows deviated range of movement during the time points in which healthy participants show less explicit control of their body positions, and requires more consistent trajectories during times when participants show more explicit control.**

I. Introduction

In developed countries, the aging society is a serious issue in healthcare. As life expectancy increases, the ratio of elderly to young individuals has been increasing rapidly [1], decreasing quality of life for both elderly and younger individuals. For elderly individuals, activities of daily life (ADL) are declined with age: transferring from the bed or chair, dressing, or using the toilet [2]. Likewise, informal family caregivers also suffer through the experience of physical and mental stress due to unaccustomed tasks [3]. In order to solve these problems, an assistive system that can enhance ADL of elderly individuals is necessary. In this study, we focus on human standing-up motion, as it has been shown that elderly individuals without enough ability to perform this basic action have difficulty in essential mobility for their ADL [4][5].

Some assistive devices have been proposed to help human standing-up motion, such as a passive gravity-balanced assistive device [6] or an exoskeleton robot suit [7]. Both methods are able to help individuals achieve their sit-to-stand motion appropriately, but the idea of preventive rehabilitation has not been adequately considered. In order to prevent individuals from being bedridden, not just complementing their deficient force but retraining their motor control becomes more important.

We have previously developed a force assistance device to enable individuals to stand up by leading them to a desired body trajectory [8]. If the system force sensor detects overload of the knee joint, it can then select an appropriate control method to support the user. By using the system, the load of the knee joint is reduced to just the amount that the elderly individuals can manage with their remaining physical force. When the measured force is less than the threshold of switching the control method, the system emulates a fixed single trajectory that is extracted from the motion of a nursing specialist. However, recent neurorehabilitation research suggests that trajectory variance is preferred over a fixed trajectory [9]. Therefore, it is important to allow the assisting system to move the user over a varied trajectory. It is possible to allow a set deviation about the fixed trajectory of the standing-up motion. However, a more refined approach would be to allow increases in trajectory variation as a function of the typical explicit control utilized during healthy standing-up motion. Understanding this explicit control would allow the development of a new control method for force assisting systems that would move consistently in the controlled phases requiring explicit attention, and with more deviation during uncontrolled phases with less explicit control.

In order to divide the motion into phases, such as controlled phases (under explicit control) and uncontrolled phases (not under explicit control), uncontrolled manifold (UCM) analysis [10] was applied to human standing-up motion. A previous study also analysed human standing-up motion [10], but the main purpose of that study was to validate the analysis method. The previous research indicated that individuals coordinated their joints in order to mainly control center of body mass rather than head or hand positions. However, only limited points of the motion were investigated and those findings were not directly applicable to our force assistance system.

In this study, we performed experiments to obtain trajectory data from both young and elderly human subjects. Our objective is to investigate how healthy individuals coordinate their joints to achieve a standing-up motion by UCM analysis. Based on our findings, we suggest a new method for controlling our force assistance system.

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II. METHODS

A. Force Assistance System

Fig. 1 shows our previously-developed force assistance system. The system consists of two components: the bed system that can move vertically and the support bar with two degrees of freedom to move vertically and horizontally. The bed system and support bar are actuated by three linear actuators (Act 1-3). The system can lift up individuals weighing up to 150 kg.

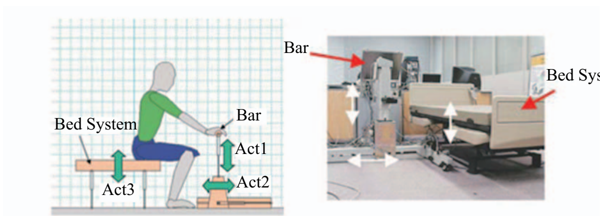

Fig. 1. (a) Schematic of how each component of the system moves. The bed moves vertically, and the bar can move both vertically and horizontally. (b) Actual assistive system. [8]

To use the system, individuals sit on the bed and grip the bar with their hands (illustrated in Fig. 1-a). The bed system can control their vertical hip position and the support bar can lead their shoulder in both vertical and horizontal directions.

The system has three degrees of freedom controlled by three independent actuators. Every 1ms, each actuator sends position information to the integrated controller and moves according to a track reference. The integrated controller receives position information from both the bed system and the support bar, and sends a new desired position to the controller of each linear actuator every 20 ms. Therefore, in order to move the system, it is necessary to provide the desired motion trajectory for each actuator.

B. Experiments

1) Experimental Setup: In our experiments, participants were asked to perform a standing-up motion. At the beginning of each trial, they were told to keep their foot angle at 80 deg, keep their back straight, and keep their arms crossed in front of their chest. Data were recorded for 7 s, and participants started standing up at the instruction approximately 2 s after recording of data started. For each participant, 9–19 trials of data were obtained.

Motion trajectory data were recorded at four points of the body using a motion capture system [HMK-200RT; Motion-Analysis]: ankle, knee, hip, and shoulder (Fig. 2-a). Although 3D motion data were obtained, a 2D link model was used in this study. The sampling rate was 64 Hz and three joint angles, $\theta_{i=foot,knee,hip}$, were calculated based on the 2D geometric link model displayed in Fig. 2-b. Our geometric 2D link model was used to calculate joint angles and the center of mass. For the length of each link, actual measured values were used, and link masses were calculated from standard body data [11].

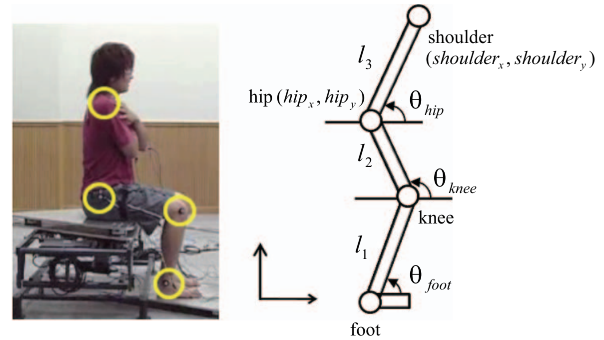

Fig. 2. (a) Yellow circles indicate locations of motion capture sensors. (b) Link model used in our study with three joint angles and four body positions.

2) Data Processing: The standing-up motion was divided into four phases, and the start points for each phase were defined as follows [12].

- Flexion momentum phase (phase 1): begins at time of first shoulder movement in the horizontal direction.
- Momentum transfer phase (phase 2): begins at time of first hip movement in the vertical direction.
- Extension phase (phase 3): begins when foot angle, θ_{foot}, achieves minimum flexion.
- Stabilization phase (phase 4): begins when the vertical shoulder position achieves its maximum.

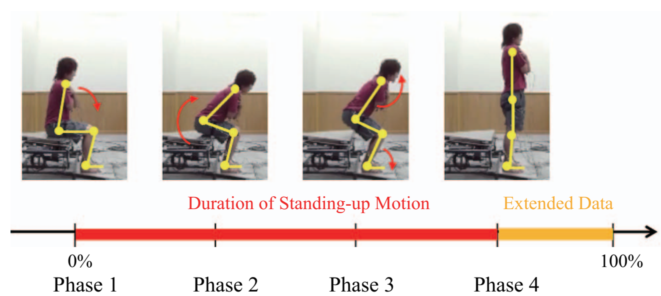

Fig. 3. Four phases of the standing-up motion: flexion momentum, momentum transfer, extension, and stabilization.

The end of Phase 4 was determined by extending the time series past the beginning of phase 4 by an additional 20% of the duration of phases 1 - 3. In addition to the phase division, all data of the motion were normalized to 100% based on the total movement time in order to compare across trials. For the normalization, the beginning point of the motion was determined at the start of phase 1 and the end of the motion was decided based on the end of phase 4.

3) Participants: 10 participants (5 males and 5 females) participated in our experiments. Participants were divided into two groups: N = 3 young (mean age 22.0 yrs, SD=0.0 yrs) participants and N=7 elderly (mean age 70.4 yrs, SD=8.6 yrs) participants.

C. UCM Analysis

UCM analysis is applied to our data in order to understand which phases of body movement are explicitly controlled and which are not. The analysis method aims to elucidate how each joint angle is coordinated to achieve a specific task. For instance, in order to achieve a specific hip height, $hip_y(t)$ derived from the geometric link model, Fig. 2-b, and (1) at a certain time (t), there are numerous combinations of foot and knee angles, which is called UCM.

$$hip_y(t) = l_1 sin\theta_{foot}(t) + l_2 sin\theta_{knee}(t) \tag{1}$$

If the hip height is invariant in spite of two variant joint angles, it indicates that these two joints are coordinated to achieve its height. Fig. 4 shows an example of UCM analysis.

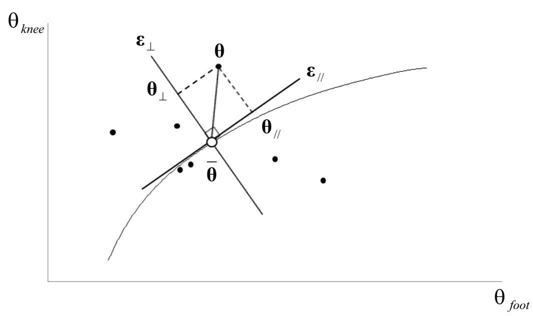

Fig. 4. Example of UCM analysis. The solid curved line indicates a UCM that achieves a specific hip height. From the average joint angle, $\overline{\theta}$, displayed as the white circle, both two vectors can be derived: the tangent vector, $\varepsilon_{//}$, and the orthogonal vector, $\varepsilon_{\perp}$. Each joint data point is projected into those two vectors, and degree of coordination is determined as a ratio of those two projected vectors.

In order to obtain UCM, Jacobian of the hip height at a specific one joint configuration must be calculated from the geometric link model (2), which indicates how hip_y will be changed according to difference of the joint angles around it. If the null space of the Jacobian, $\varepsilon_{//}$, is calculated by (3), it expresses joint space that does not change the hip height; such as UCM (solid curve line in Fig. 4). On the other hand, a vector perpendicular to the null space affects the height of hip; this is defined as $\varepsilon_{\perp}$.

$$\mathbf{J}_{hip}(\theta(t)) = \begin{pmatrix} l_1 cos\theta_{foot}(t) & l_2 cos\theta_{knee}(t) \end{pmatrix} \tag{2}$$

$$\mathbf{J}_{hip}(\theta)(t) \cdot \varepsilon_{//}(t) = 0 \tag{3}$$

In order to calculate the degree of joint coordination at time t, the joint angle vector, θ, is orthographically-projected into two component vectors, $\theta_{//}$ and $\theta_{\perp}$: $\theta_{//}$ indicates the component parallel to $\varepsilon_{//}$, which does not affect the height; $\theta_{\perp}$ is parallel to $\varepsilon_{\perp}$, and changes the height. Both $\theta_{//}$ and $\theta_{\perp}$ are calculated via (4), (5).

$$\theta_{//}(t) = \varepsilon_{//}(t) \cdot (\theta(t) - \overline{\theta}(t)) \tag{4}$$

$$\theta_{\perp}(t) = \varepsilon_{\perp}(t) \cdot (\theta(t) - \overline{\theta}(t)) \tag{5}$$

The degree of joint coordination at time t, $S(t)$, is calculated as the ratio of parallel vector, $\theta_{//}$, to perpendicular vector $\theta_{\perp}$ by (6).

$$S(t) = \frac{|\theta_{//}(t)|}{|\theta_{\perp}(t)|} \tag{6}$$

This degree of joint coordination is calculated for the entire normalized time series (1-100%) of the standing-up motion. Since our force assisting machine can lead individuals to move both shoulder and hip positions actively, we focused on those two body parts in the analysis: shoulder and hip position in the horizontal and vertical directions (hip_x, hip_y, $shoulder_x$, $shoulder_y$ respectively). In addition to those two body parts, the center of mass (CoM_x and CoM_y) is also investigated because the standing-up motion includes drastic change of center of mass from the hip to the foot. Center of mass for both vertical and horizontal directions is calculated from the geometric 2D link model using measured link length, position of the center of gravity in each link, and proportional weight of each link [11].

III. Results

Fig. 5 shows UCM analysis results for young and elderly participants. Degree of joint coordination, $S(t)$, is averaged for young and elderly participants at each time $t (t = 1 - 100)$. The blue solid lines indicate average joint coordination of young participants while the red dashed lines indicate the average joint coordination of elderly participants . Vertical lines in each graph indicate the start point of the four phases.

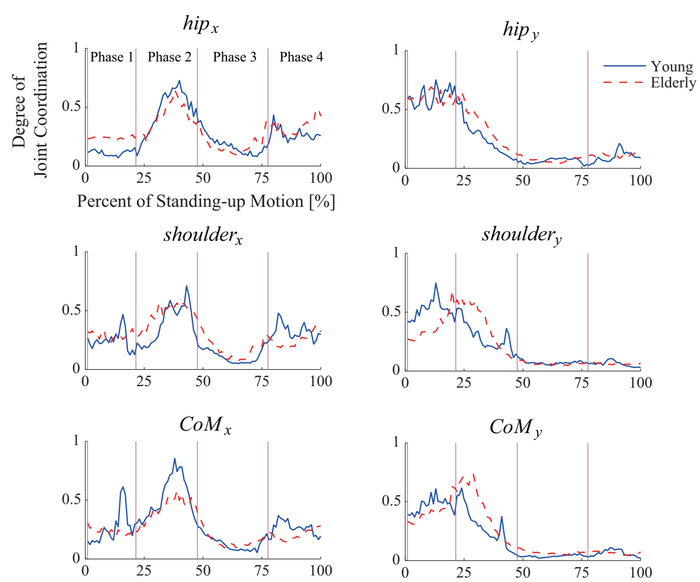

Fig. 5. Results of UCM Analysis. Degrees of joint coordination are averaged for young (blue solid lines) and elderly (red dashed lines) participants.

The results imply that both groups show the same trend of controlled variables for each phase. For hip_x, position is controlled more in phases 2 and 4 compared to the other two phases and $shoulder_x$ is controlled the least in phase 3. On the other hand, both hip_y and $shoulder_y$ are mainly controlled during the first two phases rather than the last two phases. In terms of center of mass, subjects exert more explicit control over CoM_x in phase 2 and over CoM_y in phases 1 and 2. In phase 3, all variables show less joint coordination than in the other phases.

IV. Conclusions and Discussion

Standing-up motion was studied in terms of the degree of joint coordination used to achieve the motion. UCM analysis was applied to the positions of hip and shoulder and center of mass over the entire time series of the motion.

Our results show that individuals control the horizontal position of their hip when they lift up their hip and move forward (phase 2) and when they finish lifting up their whole body (phase 4). Horizontal position of their shoulder is explicitly controlled except during the phase in which they lift up their whole body upward. These findings correspond well to the movement of their center of mass in the horizontal direction. In the first two phases, individuals must transfer their center of mass forward by bending the back and moving the hip forward. Also they need explicit control of their horizontal hip and shoulder positions in the last phase to stabilize their posture after transferring their center of mass from their hip to foot.

On the other hand, participants exert more explicit control over the vertical positions of their hip and shoulder during first two phases rather than the last two phases of the standing-up motion. Vertical movement of their center of mass is also under more explicit control only until after they transfer their momentum forward (phase 3 and after).

One finding of particular interest is that both hip and shoulder positions are less controlled in both the horizontal and vertical directions in the extension phase (phase 3). This implies that trajectories of the body extension movement can be variant since healthy individuals do not explicitly control them.

From these findings, we suggest a new control method of our force assisting system based on the degree of joint coordination. The idea is to move the system more consistently at the points when healthy individuals use more explicit control and to allow more movement variance at times when healthy individuals use less explicit control. Our proposed control scheme improves upon a fixed trajectory by providing users with the ability to use varied trajectories of motion rather than one uniform movement all the time. This methodology has the potential to enhance learning of the motion [9]. In addition, our proposed method can be employed using the existing system controller, which enables individuals with motor impairment to stand up with their remaining force in phase 3 of the standing-up motion.

Fig. 6 shows an example of our suggested trajectories provided by the new controller. While the black lines in the figure indicate average position during standing-up motion from one participant, grey areas show our suggested range of referenced movement of both hip and shoulder. The tolerant range of the suggested trajectories at time t, $\delta(t)$ is determined by (7) where $\sigma(t)$ is standard deviation at time t calculated from trials of the same participant, $S(t)$ is the degree of joint coordination for the participant, and a is a constant adjusting coefficient. This adjusting coefficient can determine how much overall deviation to allow to the averaged trajectories, and

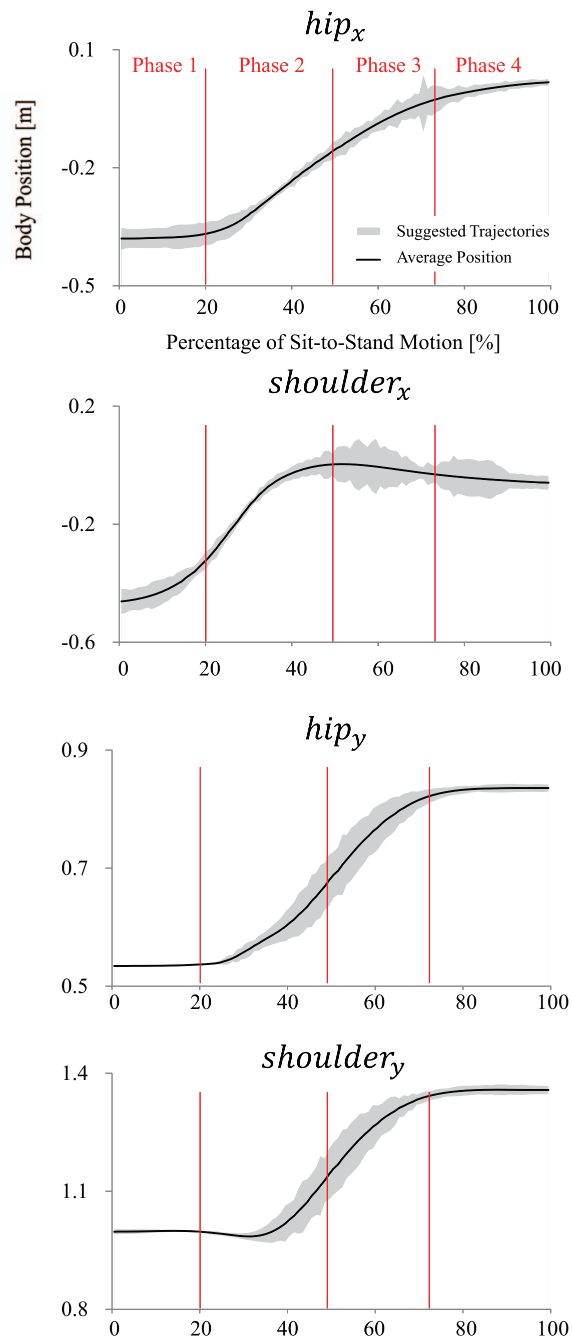

Fig. 6. Suggested trajectories of the motion for hip and shoulder positions with adjusting coefficient $a = 5$. The black solid lines show average trajectories of the motion and grey areas indicate suggested variable range of reference track trajectories for both shoulder and hip.

might be decreased if users of our system seem to tolerate deviated trajectories. In this example figure, a is set to 5.

$$\delta(t) = \frac{\sigma(t)}{aS(t)} \tag{7}$$

Our suggested method requires that the more individuals coordinate their joint angles to control their body positions, the more consistent (less variant) the suggested range of the movement becomes, and the less individuals coordinate their joint angles, the more variant the range of trajectories becomes. For instance, in phase 3 where individuals use less control of their hip and shoulder positions, our suggested ranges of trajectories are more varied than at other points. On the other hand, suggested movement ranges are very consistent for both hip and shoulder at horizontal direction. Future directions of this work will be to study the implications of this control method on our force assistance system and to test its efficacy.

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