A Model Based Analysis of Optimality of Sit-to-stand Transition

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Abstract—**Objective assessment of mobility and effectiveness of interventions remains an open issue. Timed Up and Go (TUG) and 30 Second Chair Stand (30SCS) tests are routinely used in assessing mobility of subjects, but they provide a single parameter. Instrumenting subjects with wearable sensors enables a detailed mobility assessment. Specifically, we argue that instrumented sit-to-stand (S2ST) posture transitions during the TUG and 30SCS tests can be used to assess the strength and balance of subjects. In this paper we develop a personalized three-segment model that quantifies torques/forces on the body and assesses optimality of each sit-to-stand transition. To characterize a S2ST transition we calculate action defined as an integral of mechanical energy over time. The theoretical optimal transition time can thus be determined for each person by finding the minimum action necessary for a S2ST transition. Our model assesses action during the S2ST transition using inputs from smartphone's inertial sensors, and calculates optimum S2ST transition time for a given body composition of a subject. Our experimental evaluation shows that healthy young subjects have posture transition times close to the optimal transition time generated by the model. We hypothesize that the optimality of posture transition provides an objective and potentially more accurate estimation of the mobility. We tested the model by evaluating optimum action and optimum S2ST transition time for 10 geriatric patients undergoing a mobility improvement program by comparing their performance with the optimum performance generated by the model. This paper presents the model and possible use of the results to assess long-term changes in mobility of users.**

I. Introduction

Standard assessment of mobility and fall risks of elderly include Timed Up and Go (TUG) and 30 Second Chair Stand (30SCS) tests [1]. These tests provide a single parameter, the total time to complete the TUG test and the number of posture transitions in the 30SCS test. Though useful, these parameters do not capture dynamic component of the subject's mobility. The use of wearable inertial sensors during these tests enables a more detailed assessment of mobility and fall risks of individual users.

The sit-to-stand (S2ST) postural transition is the most important phase of the TUG and 30SCS tests. It is commonly used for assessing function and strength of lower extremities, mobility, and balance in older adults [2], [3]. Previous research efforts have shown that the duration of sit-to-stand and stand-to-sit postural transitions can distinguish between older people at low and high risk for falls [4]. A slow S2ST transition requires smaller joint torques but takes more time to complete, whereas a fast S2ST posture transition requires larger joint torques but takes less time to complete.

Several studies suggest that the transition time is not sufficient to adequately describe physical impairments in older adults suffering from Alzheimer's or Parkinson's disease [5], [6]. They find that the S2ST transition represents a complex motion that requires additional parameters, such as the maximum trunk angle [7]–[9], torques on the trunk, hip and knee joints, as well as the total energy used during posture transition [10].

Therefore, by developing an analytical model of the S2ST posture transition, we can search for an optimal S2ST transition time for each subject at which he/she uses the minimum energy expenditure to make the transition. Since energy is a limited parameter in the human body, the optimum S2ST transition is very important. We calculate action as an integral of energy during posture transition and demonstrate that there is a minimum action that provides optimum posture transition time for each body composition. Our experiments indicate that physically fit subjects have spontaneous transition time very close to the optimal transition time generated by our model. Our hypothesis is that the model can provide personalized assessment of user's mobility and effects of fall prevention interventions.

We developed an mHealth smartphone application suite for mobility assessment of users [11] [12]. It uses smartphone's inertial sensors to characterize each posture transition. In this paper we present the development of the posture transition model that uses inputs from smartphone's inertial sensors to assess forces/torques and total action during posture transition according to individual body composition. We demonstrate the existence of optimum posture transition time with minimum action for each user. We assess the effect of interventions by comparing the total measured action to the optimal action for the given subject during each transition.

Section II describes the proposed mechanical model and an analysis of optimality of sit-to-stand transitions. Section III presents the results of the pilot study to assess effectiveness of mobility improvement intervention conducted by the Center for Aging in Huntsville, AL. Section IV concludes the paper.

II. Modeling of Sit to Stand Transition

We developed a simple three-segment model to evaluate dynamics and optimality of posture transitions for individual subjects. To capture dynamics of a S2ST transition we use *Action* defined as an integral of the total energy over time during the transition and measured in Js (Joule·second) [13].

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Action is calculated according to (1), where KE represents total kinetic energy of all joints, and PE is potential energy.. The optimal action for a person determines a minimum amount of energy necessary to perform the transition.

$$Action = \int_{t_{sit}}^{t_{stnd}} (KE(t) + PE(t) - PE_{sit})dt \tag{1}$$

The S2ST transition is modeled using a model that consists of three segments with masses m_1, m_2 and m_3 and lengths l_1, l_2 and l_3 as shown in the Figure 1 [14]. The l_{m1}, l_{m2} and l_{m3} are the heights of three masses m_1, m_2 and m_3 from points A, B and C respectively. θ_1, θ_2 and θ_3 are the joint angles made by the segments measured from horizontal axis. T_1, T_2 and T_3 are the torques measured in counter clockwise direction on the revolute joints A, B and C respectively. The body segments are assumed to be rigid bodies with their masses contained at Center Of Mass (COM). Segment masses and lengths ratios are taken from anthropometric data [15] and COM positions as proposed by Leva [16] and presented in Table I. During an ideal S2ST transition, angles θ_1 and θ_3 start from 90° and increase up to a maximum value and then come back to 90° again. The thigh angle θ_2 increases from zero to 90°. For a typical human body, the inertial parameters are summarized in the Table I.

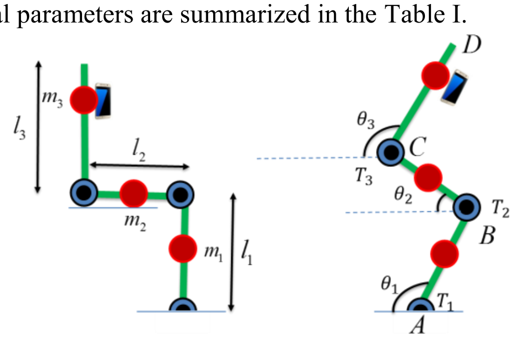

Figure 1 The three segment sit-to-stand model

The dynamics and the mathematical description of the proposed S2ST model is derived based on the principles of Lagrangian dynamics [14], [15]. The dynamic equations can be written in a compact form given in (2) [17].

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \Gamma \tag{2}$$

TABLE I. PERSONALIZED MASS AND HEIGHT DISTRIBUTION OF THE THREE LINK HUMAN BODY MODEL [15]

	Link1 (AB)	**Link2 (BC)**	**Link3 (CD)**
***m* (kg)**	13% of m	20% of m	77% of m
***l* (m)**	24% of l	26% of l	49% of l
l_m (m)	55.41% of l_1	59.05% of l_2	55.14% of l_3

$M(q) \in \mathbb{R}^{3\times3}$ is the inertia matrix which is symmetric and positive definite, $C(q,\dot{q})\dot{q} \in \mathbb{R}^3$ is the Coriolis/centripetal vector, $G(q) \in \mathbb{R}^3$ is the gravity vector, $q = [\theta_1, \theta_2, \theta_3]^T$ is a vector of joint variables, $\Gamma = [T_1 - T_2, T_2 - T_3, T_3]^T$ is the external vector-torque with T_1, T_2, T_3 being the joint torques. $M(q)$, $C(q,\dot{q})\dot{q}$, and $G(q)$ are given in (7), (8), and (9).

We use feedback linearization to linearize the system [17]. The idea is to find a nonlinear feedback control which, when substituted into (2), results in a linear close loop system. For general nonlinear systems, such a control law may be quite difficult or impossible to find. In our case, by inspecting the dynamics we see that if we choose the control Γ as equation (3), it can compensate for non-linear terms in the dynamics given in (1). The $\tilde{\Gamma}$ introduced in (3), (4) is the intermediate control in the system

$$\Gamma = G(q) + C(q,\dot{q})\dot{q} + \tilde{\Gamma} \tag{3}$$

$$\tilde{\Gamma} = M(q)u \tag{4}$$

which yields

$$\ddot{q} = u \tag{5}$$

and $u \in \mathbb{R}^3$ in (5) is the outer loop control. The output loop tracking control u drives $q \to q_c(t)$, where $q_c(t)$ is a vector reference profile. The control u is selected in a Proportional- Derivative (PD) format presented in (6).

$$u = \ddot{q}_c + K_p e + K_D \dot{e} \tag{6}$$

where, $K_P = diag\{k_{Pi}\}, K_D = diag\{k_{Di}\}, i = 1,2,3,\ e = q_c(t) - q$

The control gain matrices K_P, K_D are optimized using Linear Quadratic Optimum Control (LQOC) and the optimal gains are calculated using Riccati equation [17]. Finally the optimal control torques T_1, T_2, T_3 are computed using (10) and (11).

$$M(q) = \begin{bmatrix} (m_1 l_{m1}^2 + m_2 l_1^2 + m_3 l_1^2) & (m_2 l_1 l_{m2} + m_3 l_1 l_2)\cos(\theta_1 - \theta_2) & m_3 l_1 l_{m3}\cos(\theta_1 - \theta_3) \\ (m_2 l_1 l_{m2} + m_3 l_1 l_2)\cos(\theta_1 - \theta_2) & (m_2 l_{m2}^2 + m_3 l_2^2) & m_3 l_1 l_{m3}\cos(\theta_2 - \theta_3) \\ m_3 l_1 l_{m3}\cos(\theta_1 - \theta_3) & m_3 l_2 l_{m3}\cos(\theta_2 - \theta_3) & (m_1 l_{m1}^2 + m_2 l_1^2 + m_3 l_1^2) \end{bmatrix} \tag{7}$$

$$C(q,\dot{q})\dot{q} = \begin{bmatrix} \dot{\theta}_2^2 (m_2 l_1 l_{m2} + m_3 l_1 l_2)\sin(\theta_1 - \theta_2) + \dot{\theta}_3^2 m_3 l_1 l_{m3}\sin(\theta_1 - \theta_3) \\ -\dot{\theta}_1^2 (m_2 l_1 l_{m2} + m_3 l_1 l_2)\sin(\theta_1 - \theta_2) + \dot{\theta}_3^2 m_3 l_2 l_{m3}\sin(\theta_2 - \theta_3) \\ -\dot{\theta}_1^2 m_3 l_1 l_{m3}\sin(\theta_1 - \theta_3) - \dot{\theta}_2^2 m_3 l_2 l_{m3}\sin(\theta_2 - \theta_3) \end{bmatrix} \tag{8}$$

$$G(q) = \begin{bmatrix} g(m_1 l_{m1} + m_2 l_1 + m_3 l_1)\cos\theta_1 & g(m_2 l_{m2} + m_3 l_2)\cos\theta_2 & g m_3 l_{m3}\cos\theta_3 \end{bmatrix}^T \tag{9}$$

$$T_1 = \Gamma_1 + \Gamma_2 + \Gamma_3,\quad T_2 = \Gamma_2 + \Gamma_3,\quad T_3 = \Gamma_3 \tag{10}$$

where

$$\Gamma = G(q)C(q,\dot{q})\dot{q} + M(q)\left[\ddot{q}_c + K_p e + K_D \dot{e}\right] \tag{11}$$

The modeling and simulation was performed in Matlab Simulink (V2014). The block diagram of the S2ST feedback control system is shown in Figure 2.

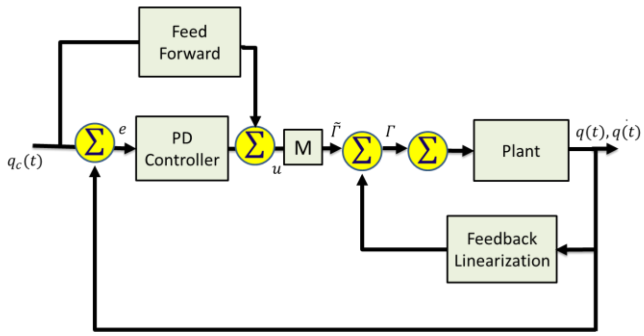

Figure 2 Sit-to-stand model and controller block diagram

We generate commands $q_c(t) = [\theta_{1c}(t), \theta_{2c}(t), \theta_{3c}(t)]^T$ in three phases: *lean forward*, *balance*, and *lift-up*. Lean forward angle $\theta_{3c}(t)$ is generated as $\sin(\pi t / T)$ during *lean forward* phase. We applied constant torque on the upper body segment with mass m_3 until center of mass of the upper body comes over the center of mass of the upper legs. At angle $\theta_{3c}(t)$ equal to $\cos^{-1}((l_2 - l_{m2}) / l_{m3})$, centers of mass are aligned, and *balance* state starts. Angle $\theta_{2c}(t)$ then varies from 0 to 90 degrees. The maximum value of $\theta_{1c}(t)$ is calculated based on the personalized balance of the whole body over the ground support point. At that moment, center of mass of the whole body is over the ground support point and *lift-up* phase begins.

Optimality of Sit-to-Stand Transition

We simulated the proposed model to calculate joint angles for a range of S2ST transition times from 0.3 to 2 s. Using these angles, we calculated the total kinetic energy ($KE = KE_1 + KE_2 + KE_3$) using (13), (14) and (15) and the total potential energy ($PE = PE_1 + PE_2 + PE_3$) using (16), (17) and (18) during each S2ST transition in the range in order to find the optimum action and the S2ST transition time.

$$KE_1 = \frac{1}{2} m_1 l_{m1}^2 \dot{\theta}_1^2 \tag{12}$$

$$KE_2 = \frac{1}{2} m_2 l_1^2 \dot{\theta}_1^2 + \frac{1}{2} m_2 l_{m2}^2 \dot{\theta}_2^2 + m_2 l_1 l_{m2} \dot{\theta}_1 \dot{\theta}_2 \cos(\theta_1 - \theta_2) \tag{13}$$

$$\begin{aligned} KE_3 = {} & \frac{1}{2} m_3 l_1^2 \dot{\theta}_1^2 + \frac{1}{2} m_3 l_2^2 \dot{\theta}_2^2 + m_3 l_1 l_2 \dot{\theta}_1 \dot{\theta}_2 \cos(\theta_1 - \theta_2) \\ & + m_3 l_1 l_{m3} \dot{\theta}_1 \dot{\theta}_3 \cos(\theta_1 - \theta_3) + m_3 l_2 l_{m3} \dot{\theta}_2 \dot{\theta}_3 \cos(\theta_1 - \theta_3) \\ & + \frac{1}{2} m_3 l_{m3}^2 \dot{\theta}_3^2 \end{aligned} \tag{14}$$

$$PE_1 = m_1 g l_{m1} \sin\theta_1 \tag{15}$$

$$PE_2 = m_2 g (l_1 \sin\theta_1 + l_{m2} \sin\theta_2) \tag{16}$$

$$PE_3 = m_3 g (l_1 \sin\theta_1 + l_2 \sin\theta_2 + l_{m3} \sin\theta_3) \tag{17}$$

We integrate KE and PE to get action for each S2ST transition using equation (1). We found the optimum S2ST transition time and optimum action by finding the minimum action from the personalized action curve as illustrated in Figure 4. An example of KE and PE values for the optimum S2ST transition time is shown in the Figure 3 (upper). Potential energy initially decreases during lean forward phase and increases more rapidly during the lift up phase. The total kinetic energy increases as a function of velocity of individual segments and falls to zero at the end of the transition. We used signals from smartphone inertial sensors during 30SCS tests and personalized parameters of the three segment model (i.e. segment lengths and masses), as input to the model. Calculated KE and PE from the personalized optimal model for geriatric patient 1006 is presented in the upper part of Figure 3, while sensor driven simulation is presented in the lower part of Figure 3. We notice that the KE and PE of the patient with limited mobility is significantly different from the optimum transition that does not consider limited strength of the user.

The required amount of action calculated for the given range of the S2ST transition times is shown in Figure 4. For example, the value of action for the S2ST transition time of 1 s is 126.1 Js. The function has a minimum that represents the optimum amount of action necessary for a person with a specific weight and height to transition from sitting to standing. Faster posture transitions require more force that might not be available in the case of the geriatric subjects. Slower transitions require less force, but more action (integral of energy in time). The values of optimum action and transition time are of great importance for diagnostic procedures since they represent a natural tendency for a subject to use minimum energy for each activity.

III. Results

We used the model to assess improvement of mobility of 10 geriatric patients with age 82±4 years. All patients attended sessions for improvement of mobility in doctor's clinic that include regular prescribed exercise regimen and management of medication guided by a gerontologist. The improvement of mobility is assessed using the standard CDC recommended tests sTUG and 30SCS. All subjects are tested at baseline, after six weeks, and after three months. The study has been approved by IRB of the University of Alabama in Huntsville.

The smartphone with the Mobility Suite application was mounted on the subject's chest for recording of inertial sensors data during 30SCS test. We used model to calculate real angles $[\theta_1, \theta_2, \theta_3]^T$ using gyroscope and accelerometer data for each stand up during 30SCS test, as well as total energy and action of each stand up during the test. The average S2ST transition time and average action for 10 subjects (subjects #2 to #11) are presented in Figure 5. Subject #1 is a healthy subject that we use for comparison with the geriatric patients.

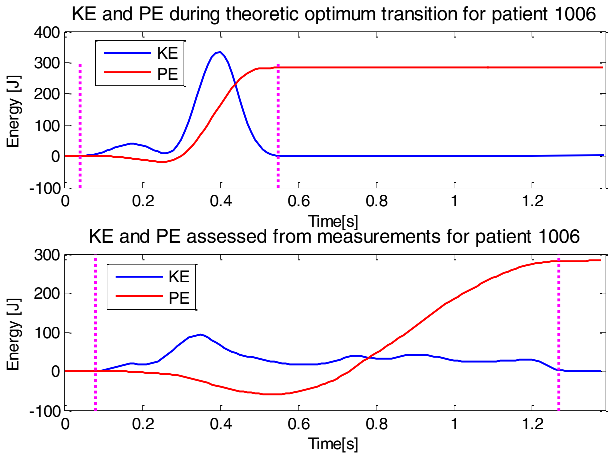

Figure 3 Demonstration of action calculation using Kinetic energy (KE) and potential energy (PE) for theoretical optimum (upper plot) and assessed from smartphone's inertial sensors (lower plot).

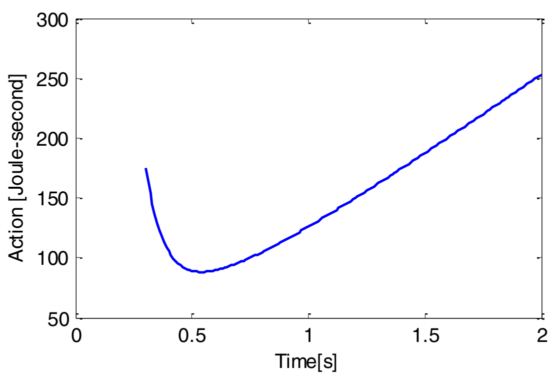

Figure 4 Variation of action with respect to S2ST transition time from 0.4-2 seconds

The reduction of average S2ST transition time and action values during intervention program demonstrates improved strength and mobility for all subjects. By focusing only on time to complete a transition, we neglect to consider body weight/composition as a parameter. Total action generated by the personalized model demonstrates promise as a parameter for assessment of effects of interventions, as indicated in Figure 5.

IV. Conclusion

Instrumentation of the standard mobility assessment tests, such as TUG and 30SCS, can provide significant information about the strength and balance of users. This is particularly important during posture transitions. In this paper we present a personalized three-segment model that quantifies torques/forces on the body and assesses optimality of each sit-to-stand transition using action. We tested the model by comparing optimum action and assessed forces of geriatric patients undergoing a mobility improvement program. The results of this study indicate that the model-based analysis has the potential to assess the mobility improvement of users over time.

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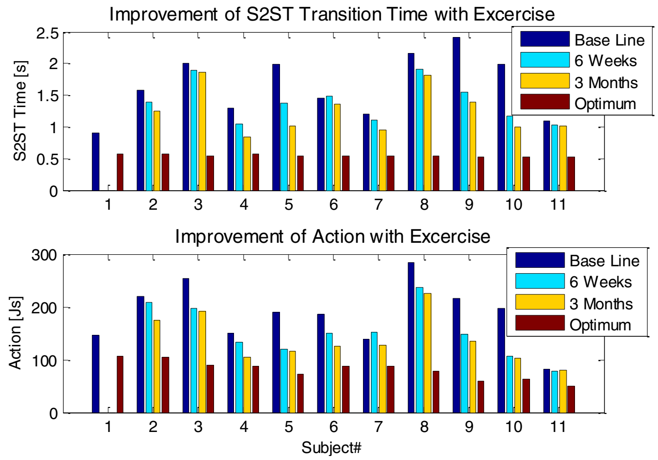

Figure 5 Improvement of mobility over time

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