椅子立ち上がり動作時に必要な最低下肢筋力の推定

The calculation of minimum required joint torque value at each lower extremity joint during the sit-to-stand movement: Computer simulation study

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1. Introduction

A sit-to-stand (STS) task is a task of standing up from a chair to an upright posture. The STS task is one of daily activities. The difficulty in achieving the STS task decreases the quality of life (QOL). In addition, the inability of the STS task needs nursing-care system and limits our independent daily living. To keep the ability of achieving the STS task helps us to keep the QOL. Therefore, it's important that the mechanisms of the STS task and the causes for the inability and difficulty are investigated and the number of the individuals for that it's impossible or difficult to achieve the STS task is decreasing.

Many factors underlie the inability and difficulty. To reveal those factors, previous researchers have studied the STS task from various points of view, such as movement speed (Gross et al., 1998; Pai and Rogers, 1991), motor strategy (Hughes et al., 1994; Papa and Cappozzo, 2000), foot placement (Khemlani et al., 1999; Shepherd and Koh, 1996), chair height (Rodosky et al., 1989), age (Alexander et al., 1991; Ikeda et al., 1991), arm movement (Carr and Gentile, 1994), trunk movement (Baer and Ashburn, 1995; Lundin et al., 1999). As the results of those studies, it has been found that the abilities of muscle strength (joint torque) and balance control are especially associated with the inability and difficulty. The knowledge from those results is valuable as the indices of the maintenance of independent living and QOL and the creation of therapeutic intervention.

However, to our knowledge, the value of minimum required joint torque at each lower extremity joint has not yet been revealed. To know the value is to know the boundary of the ability of muscle strength (joint torque) about the STS task. The knowledge is one of most important knowledge about the STS task. The knowledge about the boundary is available as the target of the rehabilitation of bedridden people and the indicator of the risk of becoming bedridden. However, to reveal the value is difficult under limited experimental conditions, such as a limited number of trials and experimental subjects, a limited range of movement speed, a limited kinds of movement pattern and so on.

Using computer simulation, we can study the value under much broader conditions in trials, movement speed and pattern compared with only experimental method. Therefore, we tried to reveal the value using computer simulation in combination with experimental method.

The purpose of this study was to calculate the minimum required joint torque value at each lower extremity joint using computer simulation.

The STS movement of this study was defined as the movement of standing up to an upright posture from a squat position in which subject’s nates touch the chair lightly. Schenkman et al. divided the STS movement into four phases (Flexion momentum phase, Momentum transfer phase, Extension phase, Stabilization phase) (Schenkman et al., 1990). The flexion momentum phase began with the start of the STS movement. The momentum transfer phase began with the time when the nates were left from a chair. The extension phase began with the time when the ankle dorsiflexion reached maximum angle value. The stabilization phase began with the time when the hip joint extension first stopped. They showed that both the hip and knee joint torque had reached maximum during the momentum transfer phase. Therefore, our definition about the STS movement seems to be appropriate for this study.

2. Method

The method of this study consisted of two steps (the Experiment step and the Computer simulation step). At the Experiment step, the database of joint angle time-series data at each lower extremity joint (hip, knee and ankle joint) was created. At the Computer simulation step, about five million movements were simulated using the database created at the Experiment step and using a human link segment model. After that, the minimum required joint torque value at each joint was determined among those movements. Those details were explained in following section.

Throughout this study, the STS movement was assumed to be the symmetry.

2.1. The Experiment step

The Experiment step is the step to create three databases of joint angle time-series data (hip, knee and ankle joint database).

Five healthy young male subjects (age (mean; 26 (SD; 3) years); height (1.74 (0.04) m); weight (73.8 (3.4) kg)) participated in this experiment. All of them had been known no musculoskeletal or neurological disorders. Each subject signed informed consent under the approval of the ethics committee of the University of Tokyo.

To get the joint angle time-series data at each lower extremity joint, the coordinates of the representative body points of subject were acquired using 3D optical motion capture system (sampling frequency; 200Hz, 7 cameras) (Hawk Digital System, Motion Analysis Corporation, Santa Rosa, CA, USA) and 7 reflective markers (right acrominon, sacroiliac joint, right and left anterior superior iliac spine, right epicondylus lateralis (defined as knee joint center), right malleolus lateralis (defined as ankle joint center), the caput of right os metatarsale quantum (defined as metatarsophalangeal joint center)). Hip joint center position were calculated from the positions of four markers (sacroiliac joint, right and left anterior superior iliac spine and right epicondylus lateralis) (Besier et al., 2003). The each joint angle was calculated from those coordinates data. The chair height used in this experiment was 0.4 m. This value was determined based on the chair for common use.

The STS movement was started from a squat position in which the nates touch the chair lightly. Subject's arms were folded across the chest. Each subject was instructed to do the STS task using various speeds and movement patterns without countermovement and arm support. The determinations of those speeds and patterns were left subjects. 50 trials were recorded each subject. Among those 50 trials, trials with countermovement were excluded. After that process, since the minimum number of trials among five subjects was 17 trials, the number of trials adopted as data was adjusted to be the same number (17 trials). 85 trials (5 subject, 17 trials each subject) were adopted.

To translate from those raw data to the data being suitable for the Simulation step, the joint angle time-series data was normalized on the movement time and the difference between the joint angle at the initial squat position and the standing position (Fig.1).

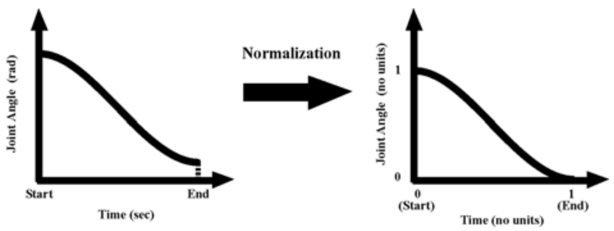


Fig.1 This figure shows the method of the normalization about the joint angle time-series data.

And, the normalized joint angle time-series data were fitted by 8th order polynomial equation. The coefficients of the polynomial equation, the movement time and the joint angle at the initial squat position were entered as one block data into the database of joint angle time-series data. That process was repeated for each joint. Using 8th order polynomial equation, we could decrease the average of residual error between the polynomial equation and the experimental data below 1 %. That was why 8th order polynomial equation was used as the fitting curve.

2.2. The Computer simulation step

The Computer simulation step is the step to determine the minimum required joint torque value at each joint using the three databases created at the Experiment step and using a human link segment model.

The human link segment model that was developed in this study consisted of four segments (head-arm-trunk (HAT), thigh, shank and foot) and three joints (hip, knee and ankle joint). A segment was connected to the next segment with frictionless mono axial hinge joint. It was assumed that slip between the bottom of the foot segment and the surface of the floor didn't occur. To get the body segmental parameter values of this model, the human data (de Leva, 1996; Winter, 1990) were scaled to fit the averages (1.74 m, 73.8 kg) of this experimental subjects' body height and weight. Only two parameter values of the foot segment (the L1 (0.0422 m) and L2 (0.1566 m) length in Fig.2b) were the averages of the measurement values of the subjects, since the values being suitable for this model couldn't be got from previous studies. Each joint angle was defined as shown in Fig.2a. The posture of which the values of all joint angles were 0 deg was defined as the model's standing position. The height of the hip joint center at the start was set the chair height (0.4 m).

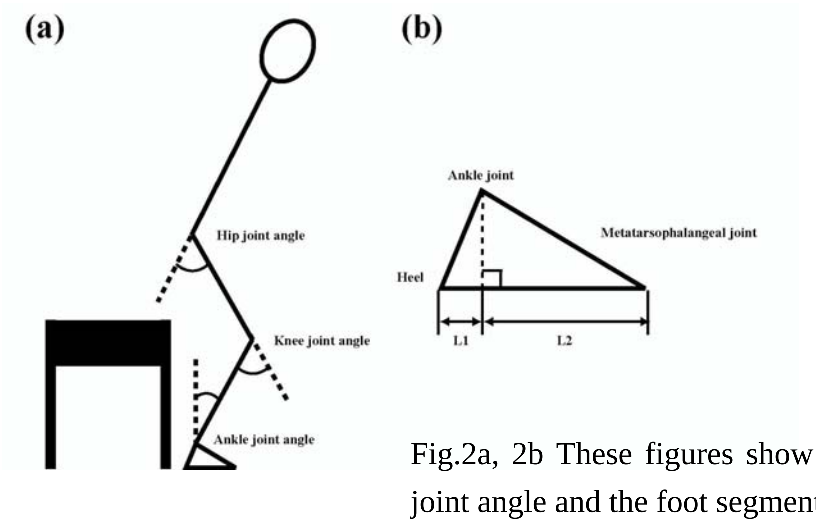
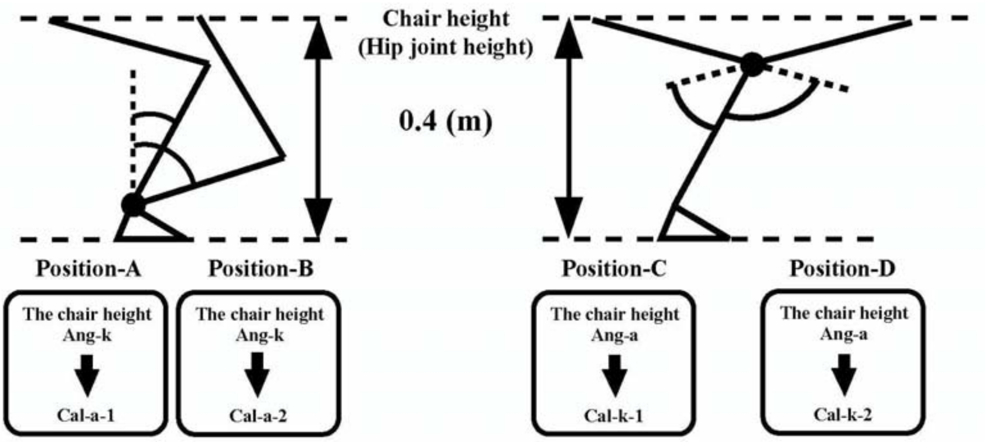


Fig.2a, 2b These figures show the definition of the joint angle and the foot segment of the model.

When an STS movement is simulated using the human link segment model and three block data contained in three joint databases, there are two problems. One is the movement times contained in the three block data are different from one another. The other is the hip joint height of the initial squat position calculated from the knee and ankle initial joint angle contained in the three block data is inconsistent with the chair height. To address former problem, three movement times were unified into one movement time. Instead of the unification, three movements were simulated under the three movement times. To address latter problem, three movements were simulated under different initial squat positions of which the hip joint height was consistent with the chair height. Those three initial squat positions were shown in Fig.3. Both the ankle joint angle of Position-A (Cal-a-1 in Fig.3) and the ankle joint angle of Position-B (Cal-a-2 in Fig.3) were calculated from the chair height (0.4 m) and the knee initial joint angle (Ang-k in Fig.3). Position-A was different from Position-B in the point of ankle joint angle. Both the knee joint angle of Position-C (Cal-k-1 in Fig.3) and the knee joint angle of Position-D (Cal-k-2 in Fig.3) were calculated from the chair height (0.4 m) and the ankle initial joint angle (Ang-a in Fig.3). Position-C was different from Position-D in the point of knee joint angle. The knee joint at Position-D was always hyperextension. Therefore, Position-D was excluded.



		Joint name		
		Hip	Knee	Ankle
The elements of the block data	the coefficients of the fitting curve	Coeff-h	Coeff-k	Coeff-a
	Movement time	Time-h	Time-k	Time-a
	The joint angle at the intial squat position	Ang-h	Ang-k	Ang-a

Fig.3 This figure shows three initial squat positions (Position-A, B, C). Position-D was excluded because of the knee joint hyperextension.

To address those two problems, nine STS movements (Table1) were simulated each combination of the model and three block data. 85 block data were contained in each joint database. Therefore, in this study, about five million (9 times the cube of 85) movements were simulated. At each STS movement, the coordinates of the center of pressure (COP) on the floor and the joint torque value at each joint were calculated. The movements of which the coordinates of the COP were not within model’s foot support range during the movement were excluded. The maximum joint torque value at each joint during each movement was recorded and plotted. Five objective functions as shown in Table2 were used as the index of each STS movement.

Table1 This table shows nine STS movements.

		Movement pattern								
		1	2	3	4	5	6	7	8	9
Movement time		Time-h	Time-h	Time-h	Time-k	Time-k	Time-k	Time-a	Time-a	Time-a
Chair height (m)		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Hip	Coefficient of fitting curve	Coeff-h	Coeff-h	Coeff-h	Coeff-h	Coeff-h	Coeff-h	Coeff-h	Coeff-h	Coeff-h
	Initial joint angle	Ang-h	Ang-h	Ang-h	Ang-h	Ang-h	Ang-h	Ang-h	Ang-h	Ang-h
Knee	Coefficient of fitting curve	Coeff-k	Coeff-k	Coeff-k	Coeff-k	Coeff-k	Coeff-k	Coeff-k	Coeff-k	Coeff-k
	Initial joint angle	Ang-k	Ang-k	Cal-k-1	Ang-k	Ang-k	Cal-k-1	Ang-k	Ang-k	Cal-k-1
Ankle	Coefficient of fitting curve	Coeff-a	Coeff-a	Coeff-a	Coeff-a	Coeff-a	Coeff-a	Coeff-a	Coeff-a	Coeff-a
	Initial joint angle	Cal-a-1	Cal-a-2	Ang-a	Cal-a-1	Cal-a-2	Ang-a	Cal-a-1	Cal-a-2	Ang-a

3. Results

Normalized joint angle time-series data at each joint (85 data) were got from the experimental step (Fig.4).

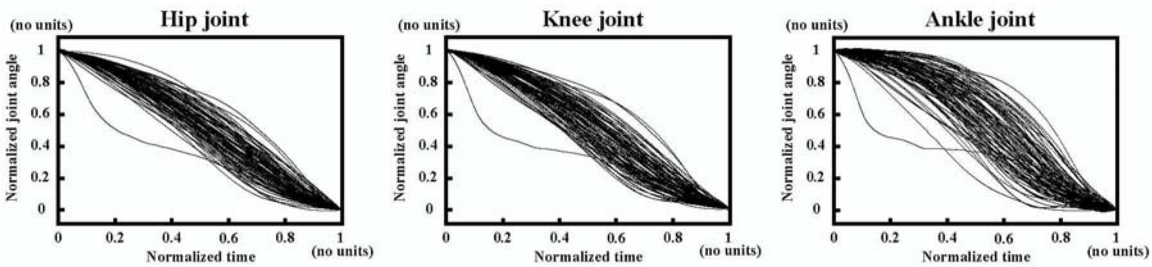


Fig.4 This figure shows normalized joint angle time-series data got from the experimental step.

One data was different from the others at the beginning of the movement. The movement time of the data was 13.03 (sec). Therefore, it was seemed the difference was attributed to the slow movement. Those data ranged in the movement time from 0.34 to 14.72 (sec). These results showed the data got from the experimental step covered both a wide range of the normalized joint angle time-series data and a wide range of the movement times. This is necessary to simulate a wide range of movement patterns.

5527125 movements (9 times the cube of 85) were simulated. 21986 movements out of all movements simulated were adopted as the successful movement. The others (5505139 movements) were excluded as the unsuccessful movement, since the coordinates of the COP were not within model's foot support range during the movement. The maximum joint torque values of each movement were recorded and plotted on the graph (Fig.5). The maximum joint torque values of the movement of which objective function value was minimum were put into Table2.

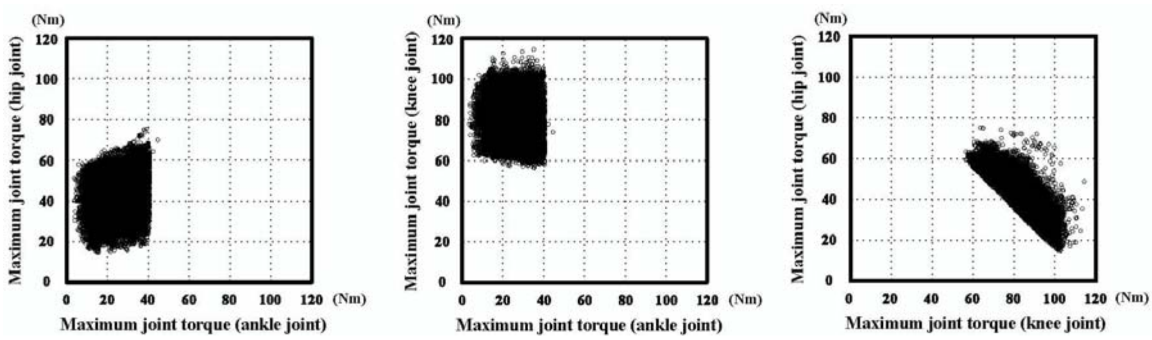
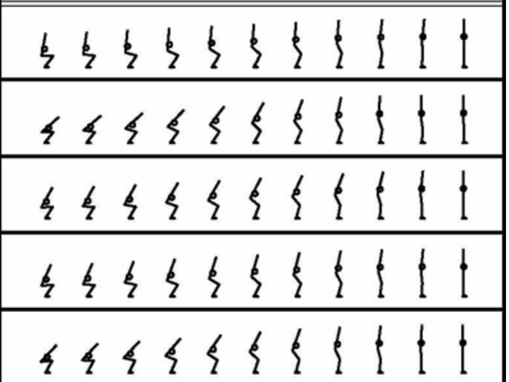


Fig.5 This figure shows the maximum joint torque values of each movement.

Table2 This table shows the maximum joint torque values of the movement of which objective function value was minimum.

Objective function	T_H (Nm)	T_K (Nm)	T_A (Nm)	Movement pattern Initial position → Standing position
T_H	14.9	102.8	14.0	
T_K	59.4	56.4	35.4	
T_A	40.3	77.8	3.6	
$T_H+T_K+T_A$	32.3	83.4	4.1	
$(T_H^2+T_K^2+T_A^2)^{0.5}$	53.3	63.1	7.1	



T_H (T_K, T_A) ······ Maximum joint torque at hip (knee, ankle) joint during the movement
Circle mark in Movement pattern ······ Center of gravity of total body

4. Discussions and Conclusion

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