Analysis of Three-Link Position Control during Sit to Stand Motion

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***Abstract*—This paper presents characteristics study of Sit to Stand (STS) motion. There are several model of STS including telescopic inverted pendulum, single-link, two-link and three-link(3L). Of all the system, 3L are chosen because of similar segment with human body. Previous study find a difficulty to analyze STS motion especially when the mass is changes. The characteristic of STS motion is not empirically conducted on the joint of each link. Hence the objective of the work presented here is to study the effect mass changes to each joint. Results shows that there is a possibility to estimate maximum torque needed by each link with equation derive from the experiment.**

***Index Terms*—Three-Link Humanoid; Sit to Stand; Mass.**

I. Introduction

In the field of rehabilitation [1], exoskeleton [2] as well as humanoid robotics [3, 4], sit to stand motion (STS) were common area where most researches running their study and experiment. The characteristic of sit to stand motion itself has not been given emphasis until recently. Most study involving recording human movement before being transferred into robot. [5].

In robotics, several works on STS were done using model of three link (3L) [6], [7], two-link elastic inverted pendulum [8] as well as single rigid pendulum [9] and telescopic inverted pendulum (TIP) [10]. The main purpose of the study includes structural stability, balance and energy transfer during STS task. From all the model mentioned, 3L model was found to be the most similar structure as human body segment and it is easy for planning and analyzing humanoid or exoskeleton robot since it directly represents the whole body motion or the COM of the robot in Cartesian space [11, 12, and 13].

Mainly in rehab facility there were some issues with prosthetic leg[14]. Some patient loss their leg due to accident, war and paralyze. Being different in body mass and length, it is hard for single prosthetic leg to be used by many patients. Each patient has difference measurement of mass and length. It is complicated for physician to adjust walking suit to fit all the patients. With this analysis, perhaps, it is plausible to make a simple calculation to estimate the max torque needed for each motor. Thus it can be used to all the patients

However, the characteristic of STS motion using 3L robotic system has never been investigated with different mass before, thus it is not clear whether simple calculation can be used to estimate the torque needed by the joint motor. For 3L model, it consists of 3 link segments represent each humanoid body, leg, thigh and upper-body[15]. For this particular reason, this paper presents a study to see the detail analysis of torque for each segment joints via experimental setup.

II. Methodology

A. Method and Strategy

In [16], STS motion were divided into two distinct phase. The phases known as forward trunk lean (CoM Transfer phase), and upward extension (standing phase), while most of other researcher redefined as three phases namely as initiation phase, seat unloading and lift off or ascending period.

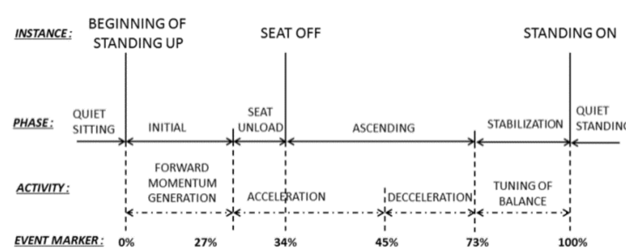


Figure 1: Stand up cycle diagram, displaying phase, activity, event marker and instance

However in 1990, [17] proposed a proper definition with terminology for defining each phases of STS motion so that the detection and separation of phases can be formalized. Figure 1, shows a typical STS cycle diagram. During the beginning of STS Cycle (0%) it is the quiet standing where the starting posture for standing up is taking form. The forward momentum represent by 27% of STS cycle. In this phase it can be considered closer to ballistic movement as it I necessary to transfer weight from seat to the feet area. During seat unload, most of the weight have been transferred to the feet and the CoM were aligned vertically to the feet to ensure stability. [11]. Right after the seat off, the ascending phase starts acceleration between 34% and 45% of the STS cycle. During this period, the whole body (WB) ascends to standing position. The vertical upward movement is ended when all the link is fully extended and it is marking the beginning of stabilization phase towards the end of STS cycle. Finally, when the WB is in total standing up position, the total cycle reach 100%.

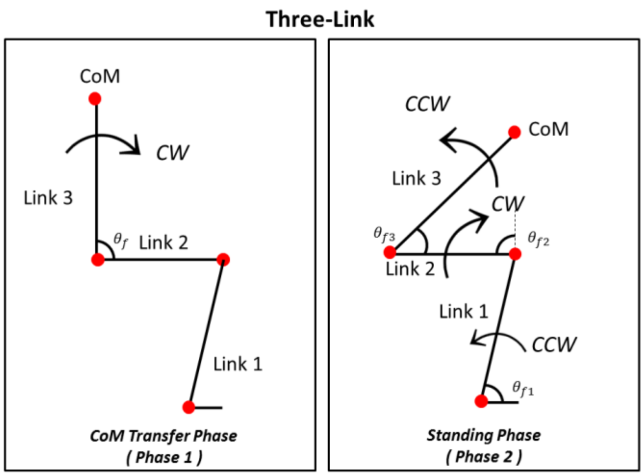


Figure 2: Illustration of each phase during STS cycle

Referring to Figure 2, it illustrates the movement of each link during both phases. In CoM transfer phase (phase 1), only link 3 is moving clockwise forward until the CoM is aligned with the support polygon [18]. θ_{fr} is the initial angle (**90°**) with respect to the link 2. Upon completing the CoM transfer phase, it continues with the standing phase (phase 2). During this phase, link 3 and link 1 is moving counter clock wise while link 2 is moving clockwise. All movement will stop when the links reach the standing position. During phase 2, θ_{fr1}, θ_{fr2} and θ_{fr3} were the initial angle with respect to the sole. In both phases link 1 is seen to be not in straight 90° position. This is due the initial setup to mimic the Alexander STS technique. This technic was known to practitioner in standing and sitting down at rehab facility. The same technic were also used by the W. Fu-Cheng, et al. [19]. The technic emphasizes on stability during the STS motion. Thus in this position, Link 1 will move counter clock wise until all link in the form of straight line.

In this application, it is applicable to use forward kinematic. It is important to know the motion of each joint, since when using inverse kinematic there is multi solution problem. We cannot be sure how the individual joint will move in order to move the end effector Center of Mass in desired Cartesian space.

For phase 1, the Centre of Mass (CoM) were assumed to bent forward. Only link 1 is involved in this STS motion. In phase 2, all link are involved. For both phases, all the joint were using cubic polynomial as it moved in forward kinematic as Equation (1) [20].

$$y(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \tag{1}$$

From Equation (1) we obtain,

$$a_0 = \theta_0 \tag{2}$$

$$a_1 = 0 \tag{3}$$

$$a_2 = \frac{3}{t_f^{\,2}}(\theta_f - \theta_0) \tag{4}$$

$$a_3 = -\frac{2}{t_f^{\,3}}(\theta_f - \theta_0) \tag{5}$$

where the value of all joint as in Table 1. All the value are respect to the goal motor position as Figure 3.

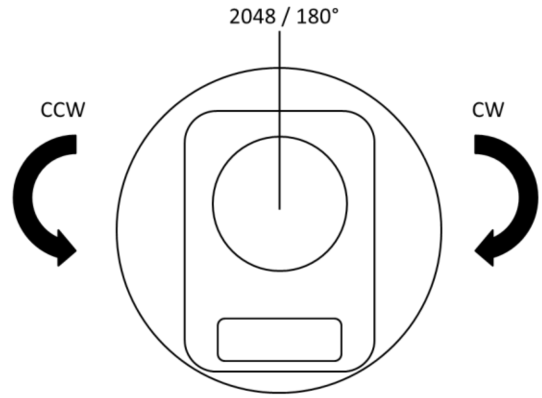


Figure 3: Illustration of Goal position in Dyanamixel motor.

Table 1
Parameter value of $\boldsymbol{\theta_f}$ **and** $\boldsymbol{\theta_0}$

Phase	θ_0	θ_f
Phase 1		
Link 3 / θ_{fr}	90°	45°
Phase 1		
Link 1 / θ_{fr1}	67°	90°
Link 2 / θ_{fr2}	90°	180°
Link 3 / θ_{fr3}	45°	180°

By substituting each value into Equation (2) – (5), we will getting the value of all joint needed. Thus, all information regarding the torque of each joint can be collected. With this information, we can estimate the max torque needed for each mass and length varied when the final equation took a form at the end of analysis.

B. Experimental setup

The experiments were setup based on the 3 link parameter, where 3 servo motor from Dynamixel were used. As for the link segment, the tough and lightweight aluminums were used according to measurement in Table 2. The link were place on the chair as Figure 3. The sole of the 3L model were placed on the floor and not mounted to the surface to simulate the human movement during STS motion. All the motor were connected to the computer receiving the value of θ_f from the MATLAB calculation. As mentioned earlier, the joint of link 1 were initially move inward into the chair to make sure the CoM is aligned when link 3 is bent forward during phase 1. The original parameter is according to the calculation based on [21, 22] in Table 2.

Table 2
Parameter of Experimental setup

Parameter	Link 1	Link 2	Link 3
L_i [m]	0.412	0.345	0.918
m_i [kg]	7.0	15.06	41.62

With respect to the experiment apparatus, since the maximum torque the Dynamixel Servo Motor can handle is upto 10 Nm, therefore, the parameter were scaled down to the limit of motor itself. Thus the value in Table 3 is the optimum parameter.

Table 3
Parameter of Experimental setup

Parameter	Link 1	Link 2	Link 3
L_i [m]	0.389	0.302	0.455
m_i [kg]	0.4550	0.6250	1.1790

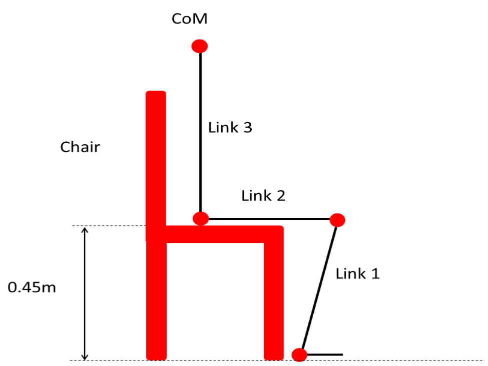


Figure 3: Illustration of 3L position on chair during STS motion

The readings for each torque were taken for mass vary. From the Dynamixel motor, the value is in current. Using performance graph provided by the Dynamixel, each value of current were converted into torque in Newton-meter.

Table 3
Parameter value of each link for varying mass

Parameter	Mass 1	Mass 2	Mass 3	Mass 4	Mass 5
Link 1 [kg]	0.3370	0.3710	0.4550	0.4890	0.5730
Link 2 [kg]	0.3890	0.5070	0.6250	0.7430	0.8610
Link 3 [kg]	0.7070	0.9430	1.1790	1.4150	1.6510

After considering the maximum torque can handle by the motor, Table 4 listed all the possible mass changes throughout the experiment. The reading were taken minimum 5 times to see the changes of torque over mass.

III. Results and Discussion

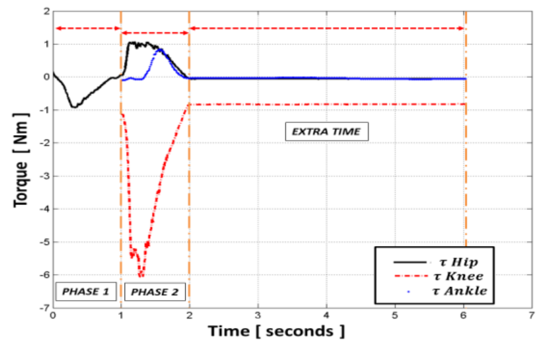


Figure 5: Torque of average mass at each joint

Figure 4 shows the results of torque for average human height and mass. The length and mass are referring to the length and mass in Table 3.

During the phase 1, only link 3 is moving since only Head Arm Torso (HAT) is bent forward while link 2 and link 1 is static. The torque of join link 3 during phase 1 ( ), is slightly going down because of the moving angle of the motor is towards negative region. It started with 0 Nm when HAT is moving forward. The acceleration of the link 3 is fast until 0.2373 seconds before it become slower towards reaching the final,   at 0.706 seconds. When link 3 reaches the desired end of the link 3 is stop for a few seconds while it stabilizes the CoM. The maximum torque needed to move the HAT forward is 0.9236 Nm at 0.2373 seconds.

As for phase 2, each joint is moving according to each angle respectively as in table 1. While link 3 continue the momentum from phase 1, link 1 and link 2 starts at -0.1202 Nm and 0.255 Nm respectively. It shows the torque is particularly high on joint of link 2 (τ_{knee_phase2}). This is due to high torque needed to bring link 2 and link 3 upward. The maximum torque needed by joint of link 2 or knee torque is -6.7542 Nm. As for joint link 1(τ_{ankle_phase2}) and joint link 3 (τ_{hip_phase2}), the maximum torque for each joint is 0.2530 Nm and 1.3819 Nm respectively. As Link 2 is moving downwards, link 1 and 3 moving upwards according to the motor movement. Link 2 accelerates until 1.708 seconds before it moving upwards towards the end. It happens due to high torque needed to lift-off the link 2 and link 3 from the chair as the weight is transfer to the sole and stabilizes [23]. For link 2, the task is resuming from phase 1. It moving upwards since the motor is moving alternately towards straight extension. The movement goes up to 1.382 seconds before it decreasing towards the end. While for link 1, the movement is only small and barely seen. Thus the torque is smallest out of all the link. The max torque for each link is described in Table 5.

Slightly after phase 2 ended, the reading is still continue to observe the behavior of each torque. It seems that, nothing changes after completion of STS motion. Thus it can conclude that torque will stop at last value when completing the standing.

Table 5
Maximum torque for each link

Parameter	Maximum Torque (Nm)
Phase 1	
Link 3	-0.9236
Phase 2	
Link 1	0.8332
Link 2	-6.064
Link 3	1.07

Next, the experiment continues with mass vary. The result as shown in Figure 5 for τ_{hip_phase1}.

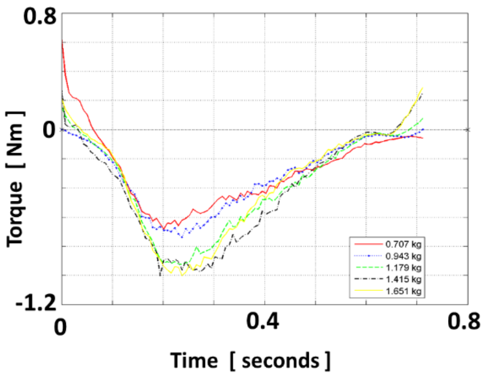


Figure 6: τ_{hip_phase1} vs time for phase 1, mass vary

Figure 6 shows the results of versus time for phase 1 when mass is varied. Clearly it is seen that the torque is reducing every time the mass is reduce from 1.651 kg to 0.707 kg.

Table 6
Maximum torque for τ_{hip_phase1}

Mass	Maximum Torque (Nm)
1.651 kg	-1.0019
1.415 kg	-1.0009
1.179 kg	-0.9236
0.943 kg	-0.7377
0.707 kg	-0.6818
1.651 kg	-1.0019

Based on maximum torque on Table 6, it shows trend of reducing from -1.0019 Nm to -0.6818 Nm parallel with the mass reducing. The negative sign indicates the magnitude of motor movement

Figure 7 below exhibits the result τ_{ankle_phase2}. It shows some inconsistency of torque reducing. This is due to the sole position when transfer of weight from hip to the sole occur, it causes some slippery. Even though some precautions have been taken, they are still some minor error when the sole become the main support for whole body when link are standing up. Another cause is, when the transfer of mass completed, the lower hip will be pulled forward right before the lift-off. When this event occur, the ankle joint will pull the HAT mass. Sometimes the initial position of lower hip will result to this event. Again, the results of maximum torque have been recorded as in Table 7

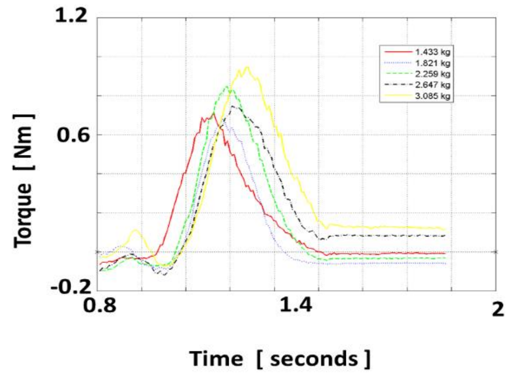


Figure 4: τ_{ankle_phase2} vs time for phase 2, mass vary

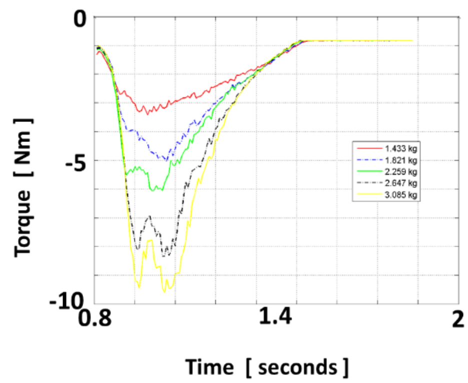


Figure 8: τ_{hip_phase1} vs time for phase 2, mass vary

Figure 8 presents the result of τ_{knee_phase2} over time. For overall timing of approximately 2.6 seconds, the torque become smaller as the mass is reducing. The maximum torque is 10.5157 Nm when the mass is heaviest compared to the other four masses. Another event can be seen from Figure 8 where two obvious spikes for mass of 3.085 Kg and 2.647 Kg. this is due the jerking of lift-off. The heavier the mass, the jerking will cause the motor to upward and downward before reaching the optimum torque to pull the HAT upward. The result of maximum torque is in Table 7.

Figure 8 is the result of torque for τ_{hip_phase2} . The torque also become smaller. From 0.8 seconds to 1.14 seconds, there are two spikes for mass of 3.085 kg, 2.647 kg and 2.259 kg. Same as τ_{knee_phase2} before, it is causes by the mass of HAT. During phase 1, the CoM is moving forward. In phase 2, link 3 will move counterclockwise to extend and standing. During this process, the mass causes the motor jerking since the control is based on position control. The motor is trying to calculate the error while maintaining the position. Slightly after 1.14 seconds, the torque is reducing almost linear towards the end of time.

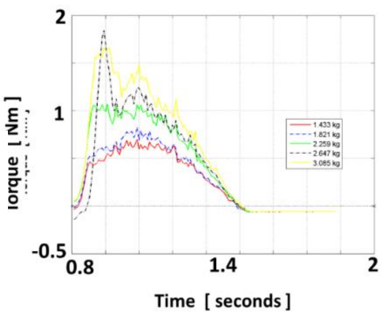


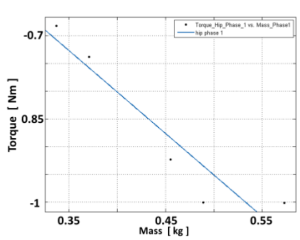
Figure 9: τ_{ankle_phase2} vs time for phase 2, mass vary

Table 4
Results of Maximum Torque for Each Joint during STS Motion

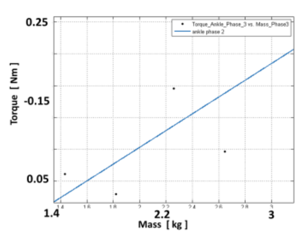
Mass	Maximum Torque (Nm)		
	τ_{ankle_phase2}	τ_{knee_phase2}	τ_{hip_phase2}
3.085 kg	0.9450	-9.6035	1.6613
2.647 kg	0.7468	-8.3433	1.8402
2.259 kg	0.8454	-6.0637	1.0700
1.821 kg	0.6798	-5.0429	0.8281
1.433 kg	0.7113	-3.4228	0.7001

In Table 7, it shows the results of maximum torque for each joint during STS motion. It is clearly shown that when the mass is reduce, the torque for each joint also reduce, except for τ_{ankle_phase2} and τ_{hip_phase1}. There is a small inconsistency. Both torque are caused by position of sole and lower hip on the chair. A minor slippery is causing this event. Since the error is small, it is possible to omit the changes and assuming the torque is reduce when mass is smaller for all joints.

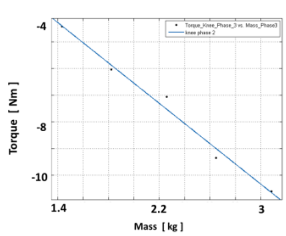
The analysis of maximum torque from table 6 and 7 were further investigated using curve fitting to find possible equation which later can be used to estimate any maximum torque when mass is varied.



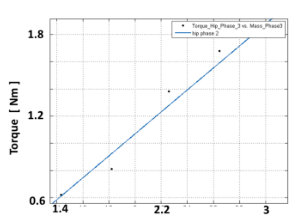
(a)



(b)



(c)



(d)

Figure 5: Curve Fitting of (a) Maximum torque of τ_{hip_phase1} (b)Maximum torque of τ_{ankle_phase2} (c) maximum torque of τ_{knee_phase2} (d) maximum torque of τ_{hip_phase2}

Figure 9 shows the result of curve fitting for all links during STS Motion. The purpose of curve fitting is to find whether all the max point is in one linear is true. Based on the R-square value as in table 8, almost all torque is closer to 1.0 except for τ_{ankle_phase2} which is not far from 1.0. With the result, it can be said that the max point in one linear line is true.

Table 5
R-Square value of curve fitting maximum torque during STS Motion

Torque	R Square Value
τ_{hip_phase1}	0.8843
τ_{ankle_phase2}	0.6249
τ_{knee_phase2}	0.9851
τ_{hip_phase2}	0.9659

From the curve fitting, we can express the equation to estimate the maximum torque for each motor based on the mass. The complete equation as Equation (6) – (9) below:

$$\tau_{hip\_phase1\_\max} = -1.499(mass_{link3}) - 0.2023 \quad (6)$$

$$\tau_{ankle\_phase2\_\max} = 0.1315(mass_{link1}) + 0.49 \quad (7)$$

$$\tau_{knee\_phase2\_\max} = -3.785(mass_{link2}) - 2.017 \quad (8)$$

$$\tau_{hip\_phase2\_\max} = 0.8081(mass_{link3}) - 0.5485 \quad (9)$$

where $mass_{link}$ is equal to the mass of each body segment.

IV. CONCLUSION

This paper presented a result of analysis characteristic for 3L model via experiment. The result shows there is a relationship between torque and mass where, each time mass is reducing, the torque also reduce. Even though for τ_{ankle_phase2} and τ_{hip_phase2} there is a little inconsistency, but it is tolerable since it is 0.1 Nm for τ_{ankle_phase2} and 0.2 Nm for τ_{hip_phase2} . Due to the fact that the sole must be in fix position and not mounted might causing a slippery to both feet and lower hip during lift-off. Even a human tend to pull back the foot a bit when try to stand. Results of curve fitting showing the capability to estimate the maximum torque needed when there is change of human mass, thus it can be used it to alter the motor needed in rehab Centre. In conclusion, it is plausible to use this method to estimate the maximum torque needed by a motor based on human weight. Thus we can reduce the faulty of the motor due to overwork when use by different patient.

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NOMENCLATURE

STS	Sit to stand
CoM	Centre of Mass
HAT	Head Arm Torso
WB	Whole Body
3L	Three-link
g	gravity
τ	Tau. Torque
phase 1	phase of Center of Mass transfer
phase 2	Phase of Standing up
τ_{hip_phase1}	Torque of joint link 3 during phase 1
τ_{hip_phase2}	Torque of joint link 3 during phase 2
τ_{ankle_phase2}	Torque of joint link 1 during phase 2
τ_{knee_phase2}	Torque of joint link 2 during phase 2