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Walking and sit-to-stand support system for elderly and disabled

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Abstract—**Walking and sit-to-stand support system, the smart mobile walker, is being developed to help elderly and disabled to live an independent daily life. It comprises almost omni-directional driving mechanism, sit-to-stand support mechanism, and motion compliance module to control the system. The development and evaluation of basic motion compliance algorithm shows that the algorithm for extraction of user intention from the interaction of the operator and the system determines performance of the system. The required parameters and performance index for improving sit-to-stand function are evaluated by the analysis of force reflection between the operator and the system. Finally, future research topics to improve the performance are addressed**

I. INTRODUCTION

Assistive technology is an umbrella term that includes assistive, adaptive, and rehabilitative devices for people with disabilities and also includes the process used in selecting, locating, and using them. It could be categorized by some key words such as mobility, access, daily living, communication, vision, etc. Due to improved welfare and medical treatment, it is anticipated that percentage of people above the age of 65 will grow strongly during the period 2010 to 2030. And it implies that percentage of population with disabilities is growing rapidly as the society is super-aged, i.e. the percentage of people above 65 is over 20%. Even though major market segments of assistive technology products are vision and communication aids, daily living and mobility aids are becoming more important for elderly to live an independent daily life. Robotic assistive technology in these categories could be distinguished as manipulation and mobility support, such as exoskeletons for disabled people, robotic wheelchairs and walkers, and navigation systems. Among these areas, robotic walking and sit-to-stand support system is considered to be the most feasible assistive product followed by robotic wheelchairs.

There are so many research areas in walking and sit-to-stand support system, including motion control algorithm [1]-[3], navigation based gait assist [4]-[6], and sit-to-stand(STS) support [7]-[10]. Gait and sit-to-stand support is evaluated by the interaction between robot and human body based on gait analysis [11]-[12] and sit-to-stand analysis [13]-[14].

This paper presents a robotic walking and sit-to-stand support system, smart mobile walker (SMW), which comprises mobile platform with drive and steering functions for semi-omni-directional motion generation including pure rotation and translation, sit-to-stand support mechanism with 6 linear actuators for trajectory generation of supporting element, and 6-axis force/torque sensor system for force feedback during walking and sit-to-stand support. Additional feature includes the stability improvement in traversing rough terrain, such as ramp, slope, bump, etc.

II. SMART MOBILE WALKER

The overview of the smart mobile walker is described in Fig. 1. It comprises drive mechanism, sit-to-stand mechanism, and motion compliance module. The drive mechanism uses front conventional DC hub-motor wheels with active brakes and high holding torque servo motors to generate translational and rotational motion, i.e. almost omni-directional function. The sit-to-stand mechanism can make 3 degree-of-freedom profile of motion with conventional 6 linear actuators and support links. The motion compliance module measures force and torque reflection between operator and system, determines intention of operator, and generates motion commands.

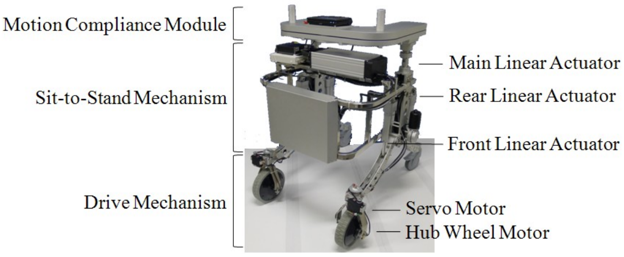

Figure 1. Overview of smart mobile walker

The motion compliance control enables the smart mobile walker to move as if it is a light passive walker with low friction, even though the robotic walker is much heavier than passive walker. Furthermore, force feedback control algorithm can make the system insensitive to the terrain condition, i.e. ramp, slope and bump.

The basic concept of sit-to-stand support considered in the smart mobile walker is illustrated in Fig.2. The sit-to-stand (STS) motion is guided by the trajectory of support plate of the system, which improves balancing and supports specified portion of weight during transition from sit to stand position.

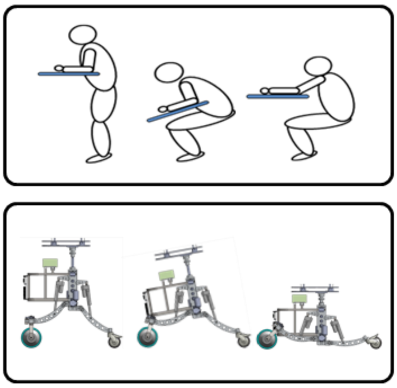

Figure 2. Basic concept of sit-to-stand support

In the walking and sit-to-stand support system, the motion of the system should be synchronized with the human behavior in accordance with the interaction between operator and system. To fulfill the requirement, motion compliance or admittance control scheme is incorporated in the system. For appropriate interaction detection during the support, 6 axis force/torque information applied to the supporting plate is required. The force-torque measurement unit shown in Fig.3 uses low cost force sensing resistor (FSR) for compression force detection and calculates 6-axis force/torque estimates according to the time responses of series of FSRs arranged around the supporting plate.

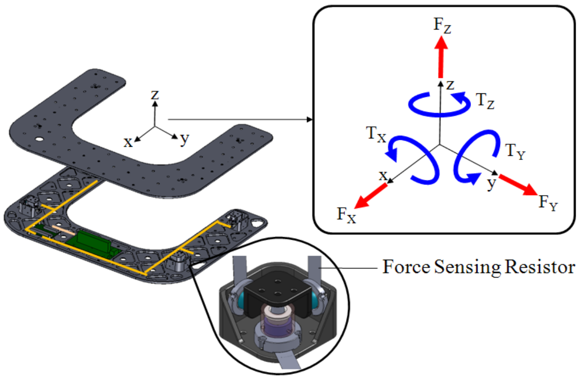

Figure 3. Force-torque measurement unit under development

In this paper conventional 6-axis force/torque sensor, ATI Omega-160, is used as reference measurement and control system design in accordance with the FSR based sensor system under development.

III. MOTION COMPLIANCE

In general, a motion is generated by the force and moment applied to the object. By assuming that force and moment applied to the walker are resulting from the force interaction between the arm of operator and the supporting plate, physical relationship of the force/torque sensor, operator, and external forces could be simplified to (1)-(3) by the model shown in Fig.4.

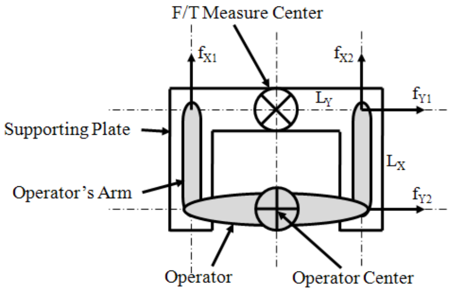

Figure 4. F/T sensor configuration

$$F_X = f_{X1} + f_{X2} \tag{1}$$

$$F_Y = f_{Y1} + f_{Y2} \tag{2}$$

$$T_Z = -(f_{X2} - f_{X1}) \cdot L_Y - f_{Y2} \cdot L_X \tag{3}$$

The dominant motions along with F_X, F_Y, and T_Z axis could be determined as shown in Fig. 5. In this application, it is assumed that the pure translation and pure rotation are switched by the pre-defined surface according to the F_X and F_Y condition and differential rotation term is added to the determined motion according to the amount of T_Z.

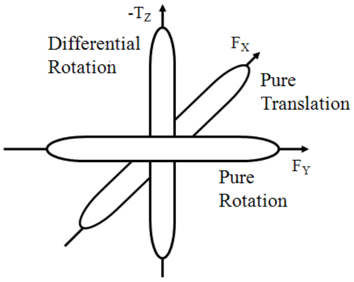

Figure 5. Relationship between force/moment and resulting motion

The linear velocity V_X and V_Y, according to F_X and F_Y respectively, and the angular velocity W_Z, according to T_Z, are calculated by (4)-(6), in which artificial drag force, F_D and T_D, and velocity damping with design coefficients, k_V and k_W, are added to make the system stop smoothly, where m_T and I_T are target mass and inertia, ΔT is sampling period, and n is the current sample number.

$$V_{X,n} = V_{X,n-1} + \left(F_{X,n} - F_D - k_V \cdot V_{X,n-1}\right)/m_T \cdot \Delta T \tag{4}$$

$$V_{Y,n} = V_{Y,n-1} + \left(F_{Y,n} - F_D - k_V \cdot V_{Y,n-1}\right)/m_T \cdot \Delta T \tag{5}$$

$$W_{Z,n} = W_{Z,n-1} + \left(T_{Z,n} - T_D - k_W \cdot W_{Z,n-1}\right)/I_T \cdot \Delta T \tag{6}$$

The numerical integration error and chattering due to sign change of drag force could be reduced by applying saturation function and high pass filtering near velocity zero range. For the pure translation, the steering angle, α, is calculated by (7), and velocity reduction of inner radius side of the differential wheel, V_{diff}, is applied by (8), where c and k are design parameters.

$$\alpha = \tan^{-1}\left(V_Y \Big/ \left(\sqrt{1+c^2W_Z^2}\cdot V_X\right)\right) \tag{7}$$

$$V_{diff} = \sqrt{V_X^2+V_Y^2} \Big/ \sqrt{1+k^2W_Z^2} \tag{8}$$

For the pure rotation, the velocities of two driving wheels should be equal in order to move along with a circle, in which radius of rotation could be changed according to the amount of W_Z. In this application, the steering angle is mechanically limited to ±85° and switching between pure rotation and pure translation could be determined by α.

In the application, the motion should be generated by the combination of the pure translation, the pure rotation and the differential rotation. To fulfill this requirement, the system uses 5 modes to generate motion in accordance with operator's intentions. In forward (FWD) mode, V_X, V_Y, and W_Z are used as state variables to calculate the driving velocity for translation, the steering angle, and the velocity difference of two driving wheels for the differential rotation. The resulting motion command is generated by the superposition of the pure translation and the differential rotation terms. As in (7), the steering angle, α, is reduced according to W_Z to obtain stable differential rotation performance with velocity differences between two driving wheels. In backward (BWD) mode, the steering angle is set to zero to improve stability, and V_X and W_Z are used as state variables to determine moving velocity including differential rotation rate. For the pure rotation, two rotation (ROT) modes are separated according to V_Y and W_Z respectively for velocity command calculation. The system stays at the idle (IDLE) mode until all integrated state variables are within the threshold levels.

Since the pure translation and pure rotation are not contiguous, i.e. motion is not smooth during change, ignoring resulting force and moment during transition is required. Furthermore, the remained integrated state variables, V_X, V_Y, and W_Z, after mode exit could induce abrupt driving velocity change when it is entering to the next mode. It results in force reflection to the operator and consequently has a possibility to amplify unwanted motion terms. To solve this problem, all integration values are reset to zero when one mode is exit to idle (IDLE) mode.

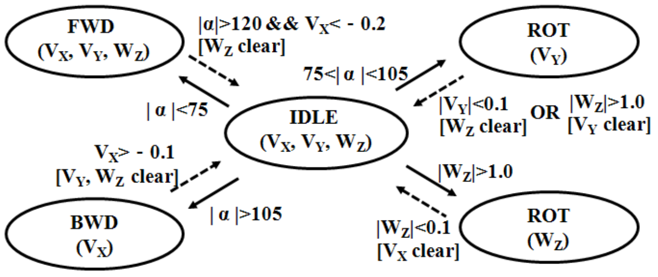

Figure 6. State diagram for mode change

It is also required that the system must exit the current mode even though the exit condition is not satisfied when the state variables for the other modes are severely bigger. In this case the mode change priority could be controlled by clearing the state variables for the current mode before exiting to the idle mode for mode change. The entering and exiting conditions for mode switching among 5 modes applied for the experiment are shown in Fig. 6, including working state variables for velocity command calculation.

In real case, force reflection between the operator and the system is complicated, because the contact condition is time varying according to the motion of the operator and the system. The response lag of the driving and the steering can cause unwanted oscillation. Furthermore, the operator can apply parasitic force or moment by leaning, gripping, hitting, rotating, etc. The time responses of the state variables and determined modes are shown in Fig. 7. In pure translation state periodic oscillation of V_X near zero value occurs due to the relative motion between the operator and the system, and it results in fluctuation of the steering angle. In differential rotation state, it is observed that the steering angle reduction according to W_Z increase makes other state variables stationary.

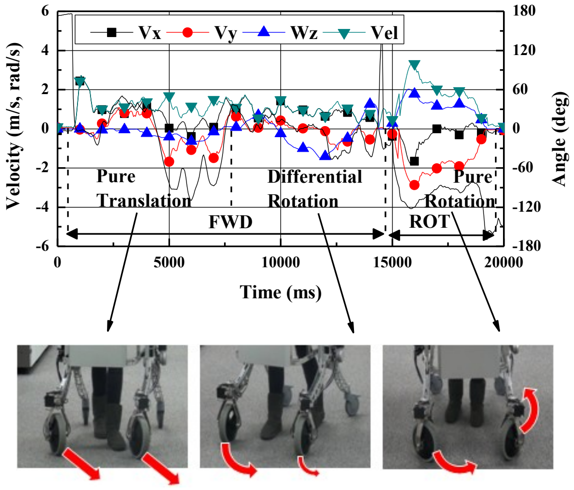

Figure 7. Time response and resulting mode switching

In the rotation (ROT) mode, working state variable is changed from V_X and α to W_Z according to the T_Z caused by operator's exertion.

IV. SIT-TO-STAND

Standing up (or sitting down) motion requires changes in the center of gravity from hip in seated state to foot in stand state (or from foot in stand state to hip in seated state). During the transition of two stationary points, body balance must be maintained. Leaning or holding support element can improve balancing by adding support points. In addition to balancing improvement, it would be helpful if the shoulder is guided by supporting element holding specified portion of body weight during the sit-to-stand motion. The trajectory of the supporting element is critical factor to determine sit-to-stand support performance [7]. In this paper, two candidate trajectories are evaluated to find out dominant parameters and performance index prior to the development of trajectory generation scheme based on optimization technique. Trajectories are expressed in local coordinate of sit-to-stand support mechanism of the system, in terms of the length of main, front, and rear linear actuators. Two candidate trajectories are plotted in Fig. 8. Major difference between two trajectories is the angle of the body during the transition. The trajectory (a) in Fig. 8 maintains trunk angle almost parallel to gravitational axis and the trajectory (b) exerts inclination of trunk to forward direction.

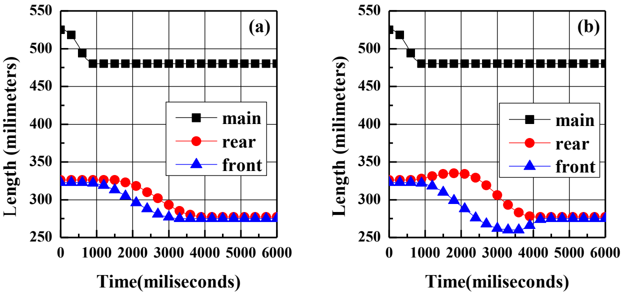

Figure 8. Two candidate trajectories for sit-to-stand support

To evaluate the characteristics of candidate trajectories, motion measurement and analysis are carried out. During the motion capture, the force plate responses of the seat and foot of the operator and force/torque sensor responses in the supporting element for arm rest are simultaneously measured. In addition, electro-myograph (EMG) signals in lower limb are also measured for further analysis. The marker position and EMG patch positions are shown in Fig. 9.

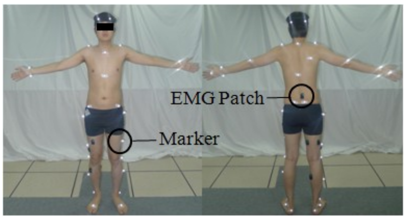

Figure 9. Marker and EMG patch configuration

In this paper, the candidate trajectories could be evaluated with the analysis of the force plate and the force/torque sensor responses during the sit-to-stand motion.

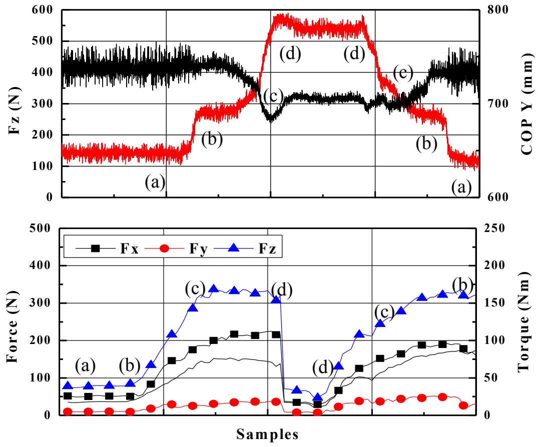

Figure 10. Force plate(upper) and F/T sensor(lower) response for candidate trajectory (a)

The time responses of force reflection during sit-to-stand using the candidate trajectory (a) and resulting motion images are shown in Fig. 10 and Fig. 11, in which (a)-(d) are same time instances. It is observed from the result that COP (coordinate of force application point) Y of the force plate is suddenly changed in (b)-(c) region and torque of force/torque sensor is about 100Nm in (c)-(d) and (d)-(c) region. It represents that balancing is maintained by the external support of the elbow, as shown in Fig. 11 (c).

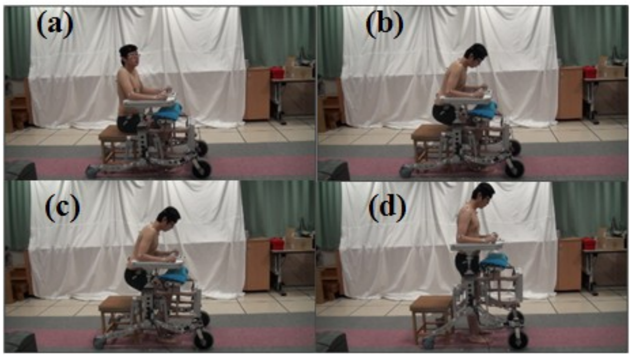

Figure 11. Sit-to-stand motion for candidate trajectory (a)

For the candidate trajectory (b), related time responses are given in Fig. 12 and Fig. 13. It could be observed that COP Y variation is small comparing to the trajectory (a) result, which shows that balancing during the sit-to-stand motion is more stable in the trajectory (b). The support of balancing at elbow results in 50Nm in (b)-(c) and (c)-(b) region, which is almost half of the value in trajectory (a). It is also noticeable that COP Y is moved to positive position at the start of (b)-(c) region, which results in stable balancing during the sit-to-stand transition.

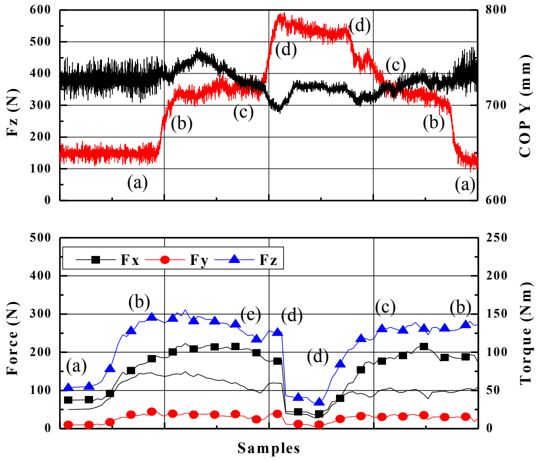

Figure 12. Force plate(upper) and F/T sensor(lower) response for candidate trajectory (b)

Comparing Fig. 11 (c) and Fig. 13 (c), it could be found that the candidate trajectory (b) shows better performance in balancing by the inclination of the body trunk. Furthermore, inclining the trunk reduces the load of knee during sit-to-stand motion [14].

By the evaluation of two candidate trajectories using the force reflection analysis, it is found out that COP Y can be a key performance index for assessing balancing maintenance. Torque of force/torque sensor should be maintained to small value for smooth balancing during the sit-to-stand motion. The flatness of F_Z and F_X in the force/torque sensor in the weight support region of the sit-to-stand trajectory is required to reduce COP Y variation during the transition.

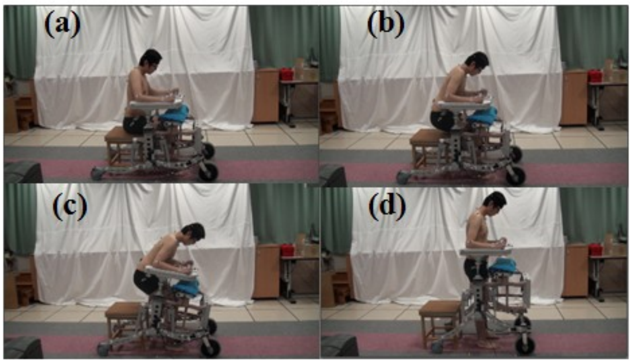

Figure 13. Sit-to-stand motion for candidate trajectory (b)

V. FUTURE WORK

To improve the performance of the walking and sit-to-stand support system, driving motor wheel and linear actuator should be improved in the response time, the position measurement accuracy, the driving noise, the compactness and output force. To fulfill these requirements, we are now developing the in-wheel motor with the suspension mechanism and high performance silent linear actuator module. The improvement of structure design can reduce the weight of the system, which plays important role in the response time improvement.

It is also required that the low cost motion compliance module with allowable force and torque measurement performance should be developed in parallel to the algorithm development for determining the intention of the operator in the system. The improvement of the motion compliance in the rough terrain environment can be another appealing function of the robotic walker. Furthermore, next research topic could be the development of optimal trajectory generation and force feedback algorithm for reliable sit-to-stand support.

VI. SUMMARY

The new robotic walker is developed to support walking and sit-to-stand motion for elderly and disabled. The motion control algorithm and the state transition diagram for operating mode change are developed and evaluated. Furthermore, two candidate trajectories for sit-to-stand support are evaluated to determine the key index for performance assessment and to characterize related parameters for the improvement in supporting body balancing and load reduction during the sit-to-stand.

ACKNOWLEDGMENT

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REFERENCES

[1] Yasuhiro Nemoto, Saku Egawa, Atsushi Koseki, Shizuko Hattori, Takeshi Ishii, Masakatsu Fujie, “Power-assisted walking support system for elderly”, Proceedings of the 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, vol. 20, no.5, pp. 2693-2695, 1998.

[2] Aiman Musa M. Omer, Hedeki Kondo, Hun-ok Lim, Atsuo /takanishi, “Development of walking support system based on dynamic simulation”, Proceedings of the 2008 IEEE International Conference on Robotics and Biomimetics, pp.137-142, 2009.

[3] Kai-Tai Song and Chen-Yang Lin, “A New Compliant motion control design of a walking-help robot based on motor current and speed measurement”, Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4493-4498, 2009.

[4] C. Schaeffer and T. May, “Care-o-bot: a system for assisting elderly or disabled persons in home environments”, Proceedings of AAATE-99, pp.340-345, 1999.

[5] Matthew Spenko, Haoyong Yu, and Steven Dubowsky, “Robotic personal aids for mobility and monitoring for the elderly”, IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 14, no. 3, pp.344-351, September 2006.

[6] D. Rodriguez-Losada, F. Matia, A. Jimenez, G. Galan, and R. Lacey, “Implementing map based navigation in guido, the robotic smart walker,” in Proc. IEEE Int. Conf. Robot. Autom, Barcelona, Spain, pp. 3401–3406, 2005.

[7] Kiyoshi Nagai, Isao Nakanishi, and Hideo Hanafusa, “Assistance of self-transfer of patients using a power-assisting device”, Proceedings of the 2003 IEEE International Conference in Robotics & Automation, pp. 4008-4015, 2003.

[8] Masamichi Tomita, Toshio Ogiso, Yasuhiro Nemoto, and Masakatsu G. Fujie, “A study of an upper-body support arm used for assisting standing-up and sitting-down motion”, JSME Internal Journal, vol. C43, no. 4, pp. 949-956, 2000.

[9] Oscar Chuy Jr., Yasuhisa Hirata, Zhidong Wang, and Kazuhiro Kosuge, “Approach in assisting a sit-to-stand movement using robotic walking support system”, Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4343-4348, 2006.

[10] Daisuke Chugo, Tai Asawa, Takuya Kitamura, Jia Songmin, and Kunikatsu Takase, “A motion control of a robotic walker for continuous assistance during standing, walking and seating operation”, Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4487-4492, 2009.

[11] Jacob Apkarian, Stephen Naumann, and Bonnie Cairns, “A three-dimensional kinematic and dynamic model of the lower limb”, Journal of Biomechanics, vol. 22, no. 2, pp. 143-155, 1989.

[12] Lei Ren, Richard K. Jones, David Howard, “Whole body inverse dynamics over a complete gait cycle based only on measured kinematics”, Journal of Biomechanics, vol. 41, pp. 2750-2759, 2008.

[13] F. Sibella, M. Galli, M. Romei, A. Montesano, and M. Crivellini, “Biomechanical analysis of sit-to-stand movement in normal and obese subjects”, Clinical Biomechanics, vol. 18, pp. 745-750, 2003.

[14] Shinsuke Yoshioka, Akinori Nagano, Dean C Hay, and Senshi Fukashiro, “Biomechanical analysis of the relation between movement time and joint moment development during a sit-to-stand task”, BioMedical Engineering OnLine, 8:27, 2009.