Mobile Robotic Assistive Balance Trainer - an intelligent compliant and adaptive robotic balance assistant for daily living

Carlo Tiseo[1] Zhen Yi Lim[2], Cheng Yap Shee[3] and Wei Tech Ang[4]

Abstract— **Balance control probably has the greatest impact on independence in activities of daily living (ADL), because it is a fundamental motor skill and prerequisite to the maintenance of a myriad of postures and mobile activities. We propose a new rehabilitation therapy to administer standing and mobile balance control training, enabled by a Mobile Robotic Assistive Balance Trainer (MRABT). The targeted group for this initial work is post stroke patients, although it can be extended to subjects with other neurological insults in the future. The proposed system consists of a mobile base and a parallel robotic arm which provides support to the patient at the hip. The compliant robotic arm with intelligent control algorithm will only provide support and assistance to the patient when the center of mass of the body deviates beyond the predefined safety boundary, mimicking the helping hands of a parent when a toddler learns to walk. In this paper, we present our initial work in the design and kinematic analysis of the system.**

I. INTRODUCTION

Balance control is a complex skill required in almost every ADL. It is a dynamic process composed of three main strategies: the maintenance of a posture, voluntary changes of postures and reaction to external perturbations to maintain stability [1]. The human control mechanism is achieved through a synergy of different types of control allocated to different body systems and synchronized by the brain [2]. In fact, the Central Nervous System (CNS) fuses together the vestibular, proprioceptive and exteroceptive information. The resulting knowledge of the environment and human body state is used by the brain motor cortex in a feed forward control manner to plan, control and execute voluntary movements that follow predefined movement strategies. This is complemented by the cerebellum which provides models of stereotyped movements (e.g. optimizing balance while skating) and contributes to coordination, precision and accurate timing by fine tuning the motor activity.

Despite numerous studies to understand how real-time sensory information is processed by the CNS, it is still not fully understood [1][3][4]. However, it is known that sensory information is fused together in the brainstem and sent to the motor cortex to issue corrective movement commands to refine the ongoing movement. This mechanism can be regarded as a slow feedback control as it takes about 200 ms to complete [4]. The slow feedback mechanism is complemented by a fast feedback structure implemented by the spinal neurons without going through the brain. This allows a fast response based on somatosensory updates to prevent falls and trips [5].

The underlying nature of the aforementioned phenomenon makes it difficult to do a specific training of the compromised ability. This is supported by reported low performances of current technologies for lower limb rehabilitation [6], and results presented in [7] showing that patients trained on walking improved their postural balance, but not *vice versa*.

Currently, balance rehabilitation is composed of two major approaches: gait rehabilitation and postural balance rehabilitation. Gait rehabilitation consists of helping patients recover the physiological movement gait through repetitive action in a controlled environment. Examples of these devices are Lokomat (Hocoma AG, Switzerland), EVRYON (EVolving moRphologies for human-robot sYmbiOtic interactioN) and LOPES (LOwer-extremity Powered ExoSkeleton). The second approach is realised by using balancing platforms, such as the Pro-Balancer^{TM} and the Wii Balance-Board (Nintendo Co. Ltd., Japan). What these technologies have in common is the ablility to train either the gait or postural control, but not both at the same time. The biggest limitation of these technologies is that they target specific sub-problems instead of approaching the balance problem in its entirety [8][9][10][11].

To the best of our knowledge, the KineAssist^{TM} (Kinea Design, LLC, USA) is the only autonomous over ground walker that integrates balance therapy with ADL tasks in a challenging and safe environment [8][9][10][11]. The high cost and dimensions of the system limits the introduction of this technology in the clinical environment. The device also requires the presence of the therapist and thus neglects the possibility of using it outside clinical environment.

II. SYSTEM DESIGN

The time to intervene and provide support is important in balance training, especially for patients with neural insults. We hypothesize that by allowing the reflex mechanism to alter the posture before providing external balance support will have a positive impact on promoting the neuroplasticity of the damaged CNS with respect to balance control.

To promote neuroplasticity, the proposed MRABT will allow the execution of CNS controlled balance mechanism

---

[1] Carlo Tiseo is with Robotic Research Centre,Mechanical and Areospace Engineering,Nanyang Technological University,50 Nanyang Avenue N3-01a-01,Singapore 639798. `m120164 at e.ntu.edu.sg`

[2] Zhen Yi Lim is with Robotic Research Centre,Mechanical and Areospace Engineering,Nanyang Technological University,50 Nanyang Avenue N3-01a-01,Singapore 639798. `ZLIM022 at e.ntu.edu.sg`

[3] Cheng Yap Shee is with Robotic Research Centre,Mechanical and Areospace Engineering,Nanyang Technological University,50 Nanyang Avenue N3-01a-01,Singapore 639798. `CYSHEE at ntu.edu.sg`

[4] Wei Tech Ang is with Robotic Research Centre,Mechanical and Areospace Engineering,Nanyang Technological University,50 Nanyang Avenue N3-01a-01,Singapore 639798. `WTANG at ntu.edu.sg`

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

(i.e. to allow practice) before the robot intervenes to provide balance assistance. By allowing more balance practices in standing and mobile ADL, the proposed assistive rehabilitation robotic system also aims to address the long standing problem of poor skill transfer from balancing control acquired in rehabilitation setting to actual execution of ADL in their home environment.

Fig. 1. The presented system is a concept design of the robot with linear actuation of θ_2 and θ_5. It also shows how the patients will be connected to the chain and supported by it and the mobile base of the system components, like the tracking device for the relative feet position.

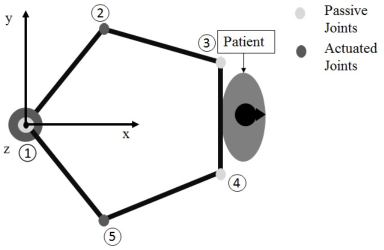

Fig. 2. The patient is connected to the link between the vertices 3 and 4 using and harness. The equilateral pentagonal chain is connected to the base between two uncoupled rotoidal joints of which one is actuated and one is passive. Moreover, the rotoidal joints in the vertex 2 and 5 are actuated, while the joints in 3 and 4 are passively driven.

This paper will focus on the initial study, design and actuation strategy of the kinematic chain interfacing the robot body with the patients. The kinematic chain also provides the interaction to support the execution of ADLs. The mobile base of MRABT and the control strategies are left to future studies.

The proposed system aims to be an autonomous multi-strategy over ground assistive device that can be used in the daily lives of people affected by the balance problem.In fact, we believe that the only way to provide people with a proper rehabilitation therapy is implementing the therapies in the assistive devices that support the everyday life of patients. In order to meet such requirements, the device needs to guarantee the safety of patients and the entities present in the surrounding environment. At the same time, it must be capable of autonomously switching between the different behavioural strategies needed to support the patients in their daily lives.

The proposed system is depicted in Fig. 1. MRABT consists of a mobile base and a parallel robotic arm which provides support to the patient at the hip. The compliant robotic arm will only provide support and assistance to the patient when the centre of mass (CoM) of the body deviates beyond the predefined safety boundary, mimicking the helping hands of a parent when a toddler learns to walk. Special attention need to be paid to the timing of balance assistance intervention in the design of the control algorithm.

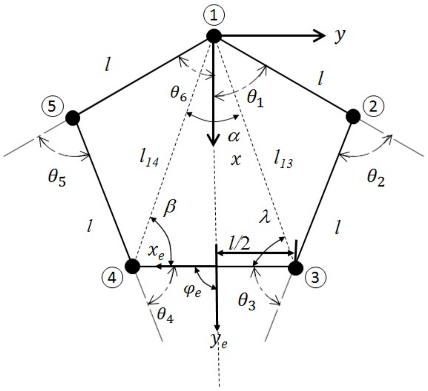

Fig. 3. The pentagonal chain is attached to the frame in the vertex 1. The actuators move the links 1-2, 2-3 and 4-5. Implying that the joint space variables are θ_1 θ_2 and θ_5. Lastly, it should be notice that in this configuration both triangles 1-2-3 and 1-4-5 are isosceles.

Our choice for the kinematic chain is based on a planar symmetrical structure with an equilateral pentagonal chain, Fig.2. This structure allows us to have 3 degrees-of-freedom (DOF) in the plane. Initially, this kinematic chain will be mounted on a static structure for testing MRABT on a treadmill. The mobile structure will only be introduced during the second stage of the development. The resultant system is a SCARA-like system, where SCARA stand for Selective Compliance Assembly Robot Arm, that is intrinsically safe for falling avoidance.

This pentagonal chain can be decomposed in two three-link planar arms where the end-effectors are attached to face each other. Linking the two arms together will create a 3-DOF planar mechanism which will be controlled through three motors assigned as shown in Fig.2. The formulation of the direct and inverse kinematics of the three planar link are reported in literature [12]. In order to be adapted to our case, we have defined the relationship of the three passive joints with respect to the active ones by making use of the geometrical relationship for the entities described in Fig.3.

- Direct Kinematic Relationships: Firstly, the distance of the vertex 3 and 4 are calculated

$$l_{13} = 2lcos(\theta_2/2) \tag{1}$$

$$l_{14} = 2lcos(\theta_5/2) \tag{2}$$

Applying the law of cosines to the triangle 1-3-4 we can compute the angles α, β and λ, Fig.3:

$$\alpha = \arccos((-l^2 + l_{13}^2 + l_{14}^2)/(2l_{13}l_{14})) \tag{3}$$

$$\beta = \arccos((-l_{14}^2 + l_{13}^2 + l^2)/(2l_{13}l)) \tag{4}$$

$$\lambda = \arccos((-l_{13}^2 + l^2 + l_{14}^2)/(2l_{14}l) \tag{5}$$

which allow to compute the unknown angles θ_6, θ_3 and θ_4

$$\theta_6 = \theta_1 - |\alpha| - |\theta_5/2| - |\theta_2/2| \tag{6}$$

$$\theta_3 = -|\pi - |\beta| - |\theta_2/2|| \tag{7}$$

$$\theta_4 = |\pi - |\lambda| - |\theta_5/2|| \tag{8}$$

- Inverse Kinematic Relationships: Given the pose of the end effector in the space $[x_e, y_e, \phi_e]^T$ we can derive the length of l_{13} and l_{14} using the coordinates of the vertices 3 and 4, Fig.3.

$$x_3 = x_e - (l/2)\cos(\phi_e) \tag{9}$$

$$y_3 = y_e + (l/2)\sin(\phi_e) \tag{10}$$

$$x_4 = x_e + (l/2)\cos(\phi_e) \tag{11}$$

$$y_4 = y_e - (l/2)\sin(\phi_e) \tag{12}$$

$$l_{13} = \sqrt{x_3^2 + y_3^2} \tag{13}$$

$$l_{14} = \sqrt{x_4^2 + y_4^2} \tag{14}$$

Substituting l_{13} and l_{14} in equations (1) and (2) allows us to compute θ_2 and θ_5, enabling the computation of θ_3 and θ_4 using equations (7) and (8). Lastly, θ_1 can be computed as in equation (15) and θ_6 substituting the result in equation (6).

$$\theta_1 = \phi_e - \theta_2 - \theta_3 \tag{15}$$

- Differential Kinematic: the Jacobian, (16), of the kinematic chain, needed to analyse the manipulability of the mechanism, has been derive applying the Dini‘s theorem to the closure equation of the chain, V, as in (17), which states that the Jacobian of a close chain is equal to the Jacobian of the closure equations respect the joint space variables, in this case θ_1, θ_2 and θ_5.

$$J = \begin{bmatrix} \frac{\partial V_1}{\partial \theta_1} & \frac{\partial V_1}{\partial \theta_2} & \frac{\partial V_1}{\partial \theta_5} \\ \frac{\partial V_2}{\partial \theta_1} & \frac{\partial V_2}{\partial \theta_2} & \frac{\partial V_2}{\partial \theta_5} \\ \frac{\partial V_3}{\partial \theta_1} & \frac{\partial V_3}{\partial \theta_2} & \frac{\partial V_3}{\partial \theta_5} \end{bmatrix} \tag{16}$$

$$V = \begin{bmatrix} x_e(\theta_1,\theta_2,\theta_3) \\ y_e(\theta_1,\theta_2,\theta_3) \\ \phi_e(\theta_1,\theta_2,\theta_3) \end{bmatrix} - \begin{bmatrix} x_e(\theta_6,\theta_5,\theta_4) \\ y_e(\theta_6,\theta_5,\theta_4) \\ \phi_e(\theta_6,\theta_5,\theta_4) \end{bmatrix} =$$
$$\begin{bmatrix} l(\cos(\theta_1) + \cos(\theta_1+\theta_2) + \frac{\cos(\theta_1+\theta_2+\theta_3)}{2}) \\ l(\sin(\theta_1) + \sin(\theta_1+\theta_2) + \frac{\sin(\theta_1+\theta_2+\theta_3)}{2}) \\ \theta_1+\theta_2+\theta_3 \end{bmatrix} - \tag{17}$$
$$\begin{bmatrix} l(\cos(\theta_6) + \cos(\theta_6+\theta_5) + \frac{\cos(\theta_6+\theta_5+\theta_4)}{2}) \\ l(\sin(\theta_6) + \sin(\theta_6+\theta_5) + \frac{\sin(\theta_6+\theta_5+\theta_4)}{2}) \\ \theta_6+\theta_5+\theta_4 \end{bmatrix}$$

The Jacobian of the chain allows to evaluate the manipulability of the chain in different configurations calculating the Manipulability Ellipsoids as in (18).

$$E(\theta_1,\theta_2,\theta_5) = J(\theta_1,\theta_2,\theta_5)[\ \dot\theta_1\ \dot\theta_2\ \dot\theta_5\ ]^T \tag{18}$$

where the velocities respect the equation (19).

$$\left[\dot\theta_1 \dot\theta_2 \dot\theta_5\right] \left[\dot\theta_1 \dot\theta_2 \dot\theta_5\right]^T = 1 \tag{19}$$

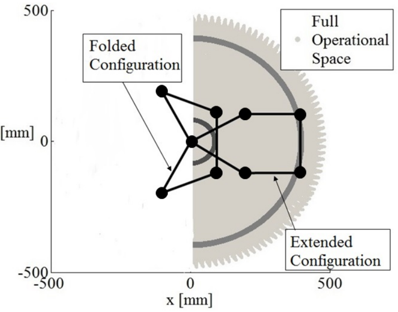

Fig. 4. The operation space for $x_e \geq 0$ is shown in the picture for a system that has the links of 250mm.

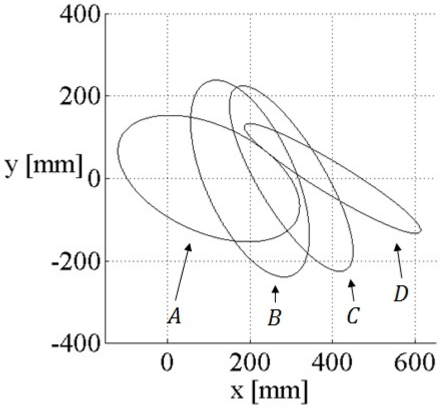

Fig. 5. The figure shows the manipulability ellipsoids in 4 different configurations, where in all four $y_e = 0$ and $\phi_e = -\pi/2$, instead x_e goes from the 150mm in A to the 400mm in D in 4 steps of 50mm each.

III. RESULTS

Using the kinematics of the chain it has been analysed both the space of the operational space,limiting our analysis to the configuration having $x_e \geq 0$, and how it is related to the link length. The Fig.4, which describes the result obtained for l=250mm, shows that the theoretical operational space includes all points of the space with a distance from the frame between the fully contracted system configuration,where $\theta_1 \approxeq -\pi$ and $\theta_5 \approxeq \pi$, and the fully extended one, where both these variables are closer to zero. Subsequently, the change of the chain manipulability has been analysed between this two configurations, Fig. 5, in order to identify a possible neutral configuration that best suits the support the patient while walking. The system has proved to be theoretically able to reach every point between 50mm from the origin (fully contracted) to about 500mm (fully extended) Fig.4. However, we have decided to limit the operational space between 150mm, fully contracted , and 400mm, fully extended, as they are shown in the figure. Because we do not want to operate near the borders of the operational space where the characteristics of the robots are distorted by the singularities. Regarding the Manipulability Ellipsoids, Fig. 5, the chain shows a good manipulability in all range with an asymmetry proportional to the chain extension. Moreover, it also presents a rotation in the Jacobian auto-engines directions,which are represented by the axes of the ellipses. In fact, the major axes gets more aligned to the x axis direction near the border of the operational space while getting closer to the y axis direction for the configuration B and C. Lastly, this figure allows to evaluate that the best configurations for walking task, where the y translation is dominant lays between B and C; while for the balancing task is better to have a configuration closer to A in order to have reduce the anisotropy of the performances.

IV. DISCUSSION

The pentagonal chain has showed to fulfil both the requirement of safety and flexibility that are required by this application, and a simple management of the singularities which has little effect on the operational space of the robot, considering that they are located in the kinematic chain extreme configurations, when $\cos(\theta_2)$, $\cos(\theta_6)$ o both of them are equal to zero. it has a wide and flexible operational space with a relatively compact configuration. In fact, considering that the human body pelvic segments' movements are constrained to very small translation and rotation during walking on a treadmill, having a maximum translation of about 30mm from the neutral position[13], we are able to obtain a sufficient operation space with a link length of 250 mm. Furthermore , this structure has the importance advantage of enabling a redundant actuation on the passive joints that allows both to reduce the actuation requirements and a greater isotropic behaviour of the system; which introduce an increasing of the cost and complexity of the system that should be carefully evaluated for the single applications.

Lastly, we want to underline the importance that the control will have on this system performances, especially due to the real time constrains introduced by both the motion tracking and the human-robot interaction. In fact, the second stage of the development, will be focusing on building a model of human behaviours in order to allow the robot to predict the patient's intentions.

REFERENCES

[1] S. Pollock, B. R. Durward, P. J. Rowe, and J. P. Paul, What is balance?, Clinical. Rehabilitation., vol. 14, no. 4, pp. 402406, Aug. 2000.

[2] F. E. Huxham, P. a Goldie, and a E. Patla, Theoretical considerations in balance assessment. Aust. J. Physiother., vol. 47, no. 2, pp. 89100, Jan. 2001.

[3] D. Winter, Human balance and posture control during standing and walking, Gait Posture, vol. 3, pp. 193214, 1995.

[4] B. Maki and W. McIlroy, Cognitive demands and cortical control of human balance-recovery reactions.,Journal of neural transmission (Vienna, Austria: 1996), vol. 114, no. 10. p. 127996, 01-Jan-2007.

[5] Zehr EP, Stein RB. What functions do reflexes serve during human locomotion? Progress in Neurobiology. 1999 Jun; 58(2):185-205.

[6] E. L. Miller, L. Murray, L. Richards, R. D. Zorowitz, T. Bakas, P. Clark, and S. a Billinger, Comprehensive overview of nursing and interdisciplinary rehabilitation care of the stroke patient: a scientific statement from the American Heart Association., Stroke., vol. 41, no. 10, pp. 240248, Oct. 2010.

[7] Barbeau, Locomotor Training in Neurorehabilitation: Emerging Rehabilitation Concepts, Neurorehabilation. Neural Repair, vol. 17, no. 1, pp. 311, Mar. 2003.

[8] I. Daz, J. J. Gil, and E. Snchez, Lower-Limb Robotic Rehabilitation: Literature Review and Challenges, J. Robot., vol. 2011, no. i, pp. 111, 2011.

[9] [J. Gil-Gmez and R. Llorns, Effectiveness of a Wii balance board-based system (eBaViR) for balance rehabilitation: a pilot randomized clinical trial in patients with acquired brain injury, J. Neurenginering Rehabilitation, vol. 8, no. 1, p. 30, 2011.

[10] W. T. Ang, U. X. Tan, H. G. Tan, T. Myo, C. K. Ng, K. L. Koh, and B. S. Cheam, Design and development of a novel balancer with variable difficulty for training and evaluation, Disability and Rehabilitation: Assistive Technology Journal, vol. 3, no. 6, pp. 325331, Nov. 2008.

[11] Tagliamonte, N.L.; Sergi, F.; Carpino, G.; Accoto, D.; Guglielmelli, E., ”Human-robot interaction tests on a novel robot for gait assistance,” Rehabilitation Robotics (ICORR), 2013 IEEE International Conference on, pp.1,6, 24-26 June 2013.

[12] B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo, Robotics: Modelling, Planning and Control (Advanced Textbooks in Control and Signal Processing), Springer-Verlag 2000

[13] J. F. Veneman, J. Menger, E. H. F. van Asseldonk, F. C. T. van der Helm, and H. van der Kooij, Fixating the pelvis in the horizontal plane affects gait characteristics., Gait Posture, vol. 28, no. 1, pp. 15763, Jul. 2008.