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Minimizing Human-Robot Interaction Force Using Proportional Derivative Compensation in Lower Exoskeleton Control

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***Abstract*—A lower extremity exoskeleton for human performance augmentation is an electromechanical structure worn by an operator and matching the shape and functions of human lower extremity leg. The exoskeleton is always in interaction with the operator during motions and integrated with human intention recognition that can increase the speed, strength, and endurance of the operator with minimal effort over type of rugged terrain. Therefore, it is important to study on human robot interaction, which will help us understand the dynamical characteristics in human and robot motions, and will improve the control quality significantly. We are also developing a lower extremity exoskeleton for human performance enhancement that called PRMI exoskeleton. In our study, the proportional derivative compensation is proposed in the hybrid control that includes position control and virtual torque control to deal with uncertainty model errors that were still limited in many previous studies. The proposed method minimizes the human robot interaction torque during human's movements. The experiment results in the paper are demonstrated and a real prototype being developed is introduced to verify our proposed methods.**

***Keywords*—Exoskeleton, dynamic model, human augmentation, human-robot interaction**

I. INTRODUCTION

An exoskeleton is a type of wearable robot that combined the skills from the wearer and power augmentation from the robot in order to perform complicated tasks easily, effectively with the aim at several applications such as infantry soldiers, rescuers, labor of burden in various environment. An exoskeleton is defined as an active mechanical device that is essentially anthropomorphic in nature, is "worn" by an operator and fits closely to his/her body, and works in concert with the wearer's movements. In general, the term "exoskeleton" is used to describe a device that augments the performance of an able-bodied wearer [1].

Exoskeleton systems can be classified into two main groups: rehabilitation active exoskeletons and human power augmentation exoskeleton.

On lower extremity exoskeletons, most researchers paid their attention to developing walking aid systems for gait disorder persons or aged people (Rehabilitations) [3-8]. However, with the aim of developing a load carrying exoskeleton whose applications in military, rescue and enhancing human's physical strength and power during locomotion, our research work focuses on human power augmentation exoskeleton system.

In this paper, the control algorithm that is integrated with physical human exoskeleton interaction is proposed based on inversed model estimation including model uncertainty compensation. By doing so, the exoskeleton shadows to the wearer's movements without feeling the exoskeleton. Much of the previous researches has been done such as in [9-11] university of Tsukuba, they have developed the mostly successful exoskeleton using for walking aid of handicapped and aged people which is named HAL. HAL system was performed according to the operator's intention by using myoelectricity (EMG) signal as primary command signal. This method is as muscle model based approaching that belongs to model based control. During operator's motion, the neuromuscular was generated and measured by surface electrodes attached on operator's skin. Based on the measured signal, the estimation of the torque exerted by flexor and extenxor can be performed as a linear function of the muscles activity. In such a way, the EMG based-controller has major disadvantages that the operator senses the discomfort while he/she is walking especially in military application this is impossible. In addition, the accuracy of the electrode will be influenced when different operator uses. Therefore, the other approaches that try to eliminate the use of EMG sensors were researched. Kazerooni and et al. developed a lower extremity exoskeleton system named as "BLEEX" using for human power augmentation at Berkeley University [12-14]. The significant contribution of their study is that the control algorithm increases the system closed loop sensitivity to its wearer's forces and torques without any measurement from the wearer [15] (such as force, position, or electromyogram signal).

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However, this control method seriously relies on the dynamic model of the system without any compensation for the model uncertainties. Therefore, their further development was enhanced in such a way that diminishes the dependence on dynamic model of the system by using hybrid control algorithm for the subsystems that separated from the whole system [16]. The whole system was separated into two systems, the first is stance leg model controlled by master-slave control and the second one is swing leg model controlled by a sensitivity amplification control (SAC). However, this method was still necessary to use an accurate model in SAC. In order to overcome this issue, Xiuxia Yang and et al. developed this method by estimating inverse dynamic models using neural network in their control algorithm [17]. Their results, however, was only verified from simulation work and the computation time is also one of aspects need to be considered in the practical application. As an alternative approach, impedance control algorithm is used for exoskeleton control. However, force sensors must be installed at human robot interface to measure the interaction force. However, it's difficult to obtain reliable measured value because the wearer is in contact with the exoskeleton at not just braces connecting locations but several locations that are undefined. In this paper, we propose a hybrid control method for a lower extremity exoskeleton named PRMI exoskeleton that we are developing. The PD control is applied to stance leg model and the virtual torque control is applied to swing leg model. However, we improve the virtual torque control by using proportional derivative compensation method to compensate model uncertainty due to estimation errors of estimated forward swing leg model.

The paper is organized into five sections: the introduction presents the background knowledge related to the paper in the first section. The second section introduces the draft mechanical design of the PRMI exoskeleton. Dynamic models and the physical human robot interaction model are built in section three. Next, the control algorithm and the simulation results are presented in the fourth section. Finally, conclusion and future works are depicted in the fifth section.

II. MECHANICAL DESIGN OF THE PRMI EXOSKELETON

According to the above definition of exoskeleton, in the consideration of the mechanical design, biomechanics of human should be investigated. The leg and foot of the human being has a total of 30 degrees of freedom (DOF).

The hip joint of a person is a ball and socket joint with three degrees of freedom. The knee is basically a hinge joint but some additional movement is possible so the joint may be considered to have two degrees of freedom. The ankle is basically a one-degree-of-freedom hinge joint but there are many degrees of freedom in the foot due to the large number of bones in the foot.

Fig 1. Anatomy of the skeletal system [18]

Fig 2. Prototype of PRMI exoskeleton

However, it is impossible to include all DOFs of human legs in consideration of design complexities. This analysis is to determine the minimum number of DOF per lower extremity that is required for both simplicity and optimum agility. Based on this, the minimum number of degrees of freedom is decided for the PRMI exoskeleton that ensures both simplicity and normal motions such as walking forward/backward, changing direction, walking in a circle, inclining, etc.

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So, the design at the foot is a plate which is located under human's foot the number of DOF is significant decreased. The each leg has a total of six DOFs in which the hip structure has three DOFs in total. They perform function of flexion/extension, abduction/adduction and internal rotation /external rotation. At the knee joint, there is one DOF which perform the flexion/extension, one DOF at the ankle permits dorsiflexion/planter flexion and one DOF at the metatarsophalangeal joint for flexion /extension, and one for rotational motion of the trunk about hip joint. So, the constructed PRMIE has a total of thirteen DOFs. This number of DOF allows PRMI exoskeleton to respond with any normal human's movements.

The PRMI exoskeleton system is shown in the Fig 2. Only flexion-extension DOF at the hip joint is actuated. The knee has one flexion-extension DOF which is actuated. Therefore, there are four DOFs in total which are actuated in preliminary work using Maxon DC motors attached with a harmonic drive gear. The other DOFs are controlled by the wearer because the motions that belong to these DOFs effect on dynamic characteristic insignificantly while flexion/extension of hip and knee is the most important to the normal walking and its energy consumption is also most, so, it is necessary to decrease the number of actuated DOFs for simplicity. Rotary encoders are located at joints to measure the joint position. In addition, air pressure sensor system is located under boot including front area and rear area on each foot to detect transition of center of gravity during walking based on the change air pressure value in a tube.

III. Dynamical Model And Physical Human Exoskeleton Interaction

An entire normal walking cycle basically has two main phases: a swing leg phase and a stance leg phase. The swing leg phase under goes larger motions but it is only supporting its own weight, it needs relatively small torques. The stance leg phase goes through a small motion but supports the entire torso and payload, it needs larger torques.

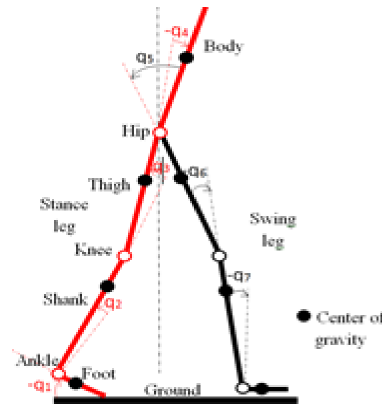

Fig 3. Stance leg model (left part), swing leg model (right part)

The total of DOFs in this study is thirteen according to the previous section. However, the dynamical characteristics are only investigated in the sagittal plane for simplification. The small motions in other plane are ignored because its effects on dynamics are insignificant. Therefore, the performed dynamical model has a total of degrees of freedom of seven as shown in the Fig 3. Due during walking, the two legs are always controlled simultaneously and alternately, each leg condition has different dynamical characteristics, therefore, the overall system should be also divided into subsystems for convenient control and it's easy to obtain a smooth walking. Based on this consideration, we build two subsystems: the stance leg model has four DOFs and the swing leg model has three DOFs.

A. Stance leg model

Stance leg model is shown as left part in Fig. 3, the dynamic equation can be written in general form as:

$$M(q_e).\ddot{q}_e + C(q_e,\dot{q}_e).\dot{q}_e + G(q_e) = T_{act} + T_{Int} \qquad (1)$$

Where $q_e = [q_1, q_2, q_3, q_4]T$ and $T_{act} = [0, 0, T_3, T_4]^T$, M is the 4×4 inertial matrix and is a function of q_e. $C(q_e, \dot{q}_e)$ is the centripetal and Coriolis matrix and is a function of q and $\dot{q}$. G is the 4×1 vector of gravitational torques and is a function of q only. T_{act} is the 4×1 actuator torque vector in which T_1 and T_2 are equal to zero, because the two degrees of freedom are not actuated but controlled by the wearer. T_{int} is the 4×1 interaction torque vector which imposes on the exoskeleton by the wearer.

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B. Swing Leg Model

By applying the Lagrange equation of motion, the dynamic equation of the swing leg model is derived as:

$$M(q_e).\ddot{q}_e + C(q_e, \dot{q}_e).\dot{q}_e + G(q_e) = T_{act} + T_{Int} \quad (2)$$

Where $q_e = [q_5, q_6, q_7]T$ is the 3×1 vector of joint positions, $T_{act} = [T_5, T_6, 0]^T$ is the 3×1 vector of applied joint torques from the actuators, $M(q_e)$is the 3×3 symmetric positive-definite swing leg inertia matrix. $C(q_e, \dot{q}_e), \dot{q}_e$ is the 3×1 centripetal and Coriolis torques, $G(q_e)$ is the 3×1 vector of gravitational. T_{act} is the 3×1 actuator torque vector in which T_7 is equal to zero, because the DOF is not actuated but controlled by the wearer. Tint is the 3×1 interaction torque vector which imposes on the exoskeleton from the wearer.

In the absence of friction and gravity, from equations (1) and (2), the interaction torques can be written as:

$$T_{Int} = M(q_e).\ddot{q}_e + C(q_e, \dot{q}_e).\dot{q}_e + G(q_e) - T_{act} \quad (3)$$

C. Physical human robot interaction

Any exoskeleton's movement always occurs in contact with the wearer. Therefore, there exist interaction forces between the wearer and the exoskeleton. In our study, we use plastic bands as physical couplings at middle of thigh and shank. So, interaction forces are exerted by the exoskeleton via these connections. Therefore, a good model describing these couplings is very important because of their great influence on control strategy.

During walking, the wearer causes the interaction torques imposing on the exoskeleton due to the deviation between q_h and q_e,.

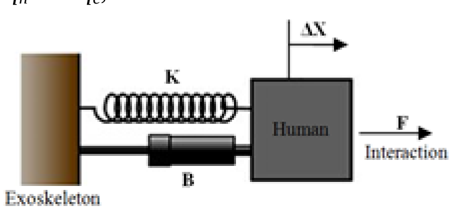

Fig 4. Spring-damper model human-robot interface

If a controller is designed so that it can control the exoskeleton's movements quickly and simultaneously in parallel to the wearer's voluntary movements, q_e approximates q_h or the interaction torque trends to zero. Therefore, the wearer seems to feel without the exoskeleton during walking. Thus, the interaction model expresses an interaction force as a function of $(q_h, \dot{q}_h, \ddot{q}_h, q_e, \dot{q}_e, \ddot{q}_e)$.

In many researches, a common interface (refer to Fig. 4) is a combination of nonlinear elastic and viscoelastic elements as compliant connection.

The interaction torque can be modeled by below formulation:

$$T_{int} = k.(q_h - q_e) + b.(\dot{q}_h - \dot{q}_e) \quad (4)$$

Where, k is stiffness coefficient, b is damping coefficient. It is not easy to get the coefficients that can model the compliant connections exactly because this model is only linear system while the human exoskeleton interaction is non-linear system. These coefficients are recognized through experimentation.

IV. CONTROL AND EXPERIMENT RESULTS

A. Control Strategy

Fig.5 shows the control scheme of PRIM exoskeleton. In this scheme, human robot interaction includes a cognitive human-robot interaction (cHRI) and a physical human-robot interaction (pHRI). The role of the cHRI is to make the exoskeleton recognize human's intention such as leg switching, etc. In other words, this is the human intention recognition block for exoskeleton while pHRI implies the physical coupling between the robot and the human, leading to the application of controlled forces between both actors. In this paper, the pHRI is mentioned as previous section, the cHRI will be mentioned in future work.

According to the discussion in previous section, the desired interaction torque should be trended to zero value during human's motion. Therefore, the proposed control strategy has to be ensured the interaction torque is very small. The basic control approaches to management of the pHRI can be classified into two groups: feed-forward control and feedback control. Feed-forward systems execute control action using a model-based estimation [17]. In this paper, a hybrid controller is built for the lower exoskeleton. It includes a PD controller for the stance leg model and a virtual torque controller for the swing leg model.

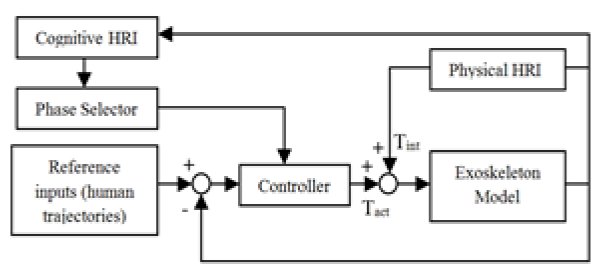

Fig. 5. Control scheme of PRIM exoskeleton

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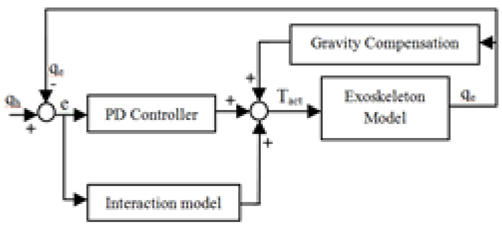

Fig 6. Position Control diagram applied to stance leg phase

PD Control for Stance Leg Model

In the control scheme, the interaction model and gravity compensation blocks are included as the Fig 6. The position control scheme applied to the stance leg model.

We design the position controller including gravity compensation as follow:

$$T_{act} = K_p.(q_h - q_e) + K_d.(\dot{q}_h - \dot{q}_e) + \tilde{G}(q_e) \qquad (5)$$

Where q_h, q_e are the angle positions of the human and the exoskeleton limbs, respectively.

$\tilde{G}(q_e)$ is the estimation of torque due to gravitation element.

Substitute (5), (4) into (1) we have:

$$M(q_e).\ddot{q}_e + C(q_e, \dot{q}_e).\dot{q}_e + G(q_e) = (K_P + k).\tilde{q} + (K_D + b).\dot{\tilde{q}} + \Delta G(q_e) \qquad (6)$$

where

$\tilde{q} = q_h - q_e, \dot{\tilde{q}} = \dot{q}_h - \dot{q}_e, \Delta G(q_e) = \tilde{G}(q_e) - G(q_e)$ is the model estimation error

We assume that the estimation of gravity element is good, that means the estimation error is very small, $\Delta G(q_e) \approx 0$, and set $K_P' = K_P + k$, $K_D' = K_D + b$, $u = M(q_e).\ddot{q}_h + C(q_e, \dot{q}_e).\dot{q}_h$, the equation (6) is rewritten as follow:

$$M(q_e).\ddot{\tilde{q}} + (C(q_e, \dot{q}_e) + K_D').\dot{\tilde{q}} + K_P'.\tilde{q} = u \qquad (7)$$

Defining the Lyapunov function

$$V = \tfrac{1}{2}\dot{\tilde{q}}^T.M.\dot{\tilde{q}} + \tfrac{1}{2}.\tilde{q}^T.K_P'.\tilde{q} \qquad (8)$$

$M(q_e)$, K_P' are positive definite matrices, V is global positive definite.

$$\dot{V} = \dot{\tilde{q}}^T.M.\ddot{\tilde{q}} + \frac{1}{2}.\dot{\tilde{q}}^T.\dot{M}.\dot{\tilde{q}} + \dot{\tilde{q}}^T.K_P'.\tilde{q}$$
$$= \dot{\tilde{q}}^T(M.\ddot{\tilde{q}} + \tfrac{1}{2}.\dot{M}.\dot{\tilde{q}} + K_P'.\tilde{q}) \qquad (9)$$

Using the characteristic of $\dot{M}(q_e) = C(q_e, \dot{q}_e)$

Equation (9) is derived as follow:

$$\dot{V} = \dot{\tilde{q}}^T(M.\ddot{\tilde{q}} + \frac{1}{2}.C.\dot{\tilde{q}} + K_P'.\tilde{q})$$
$$= -\dot{\tilde{q}}^T(K_D' + \tfrac{1}{2}.C).\dot{\tilde{q}} \qquad (10)$$

With $\|C(q_e, \dot{q}_e)\| \le \|\mu_0\|$, μ_0 can be defined, K_D' can be chosen so that $K_D' + \frac{1}{2}.C$ is positive definite. According to the Lyapunov criterion, the system is stable, the exoskeleton's motions track to the wearer's, therefore, the wearer can control with a minimum effort.

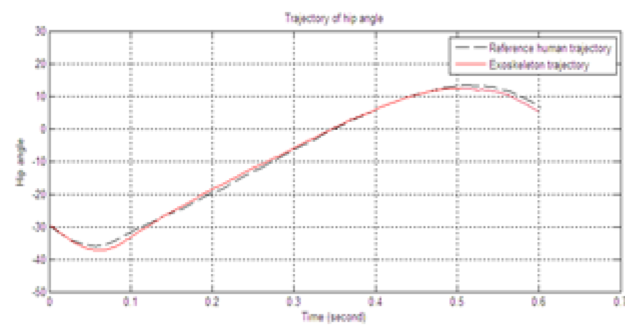

Fig 7. Trajectory of hip angle (degree)

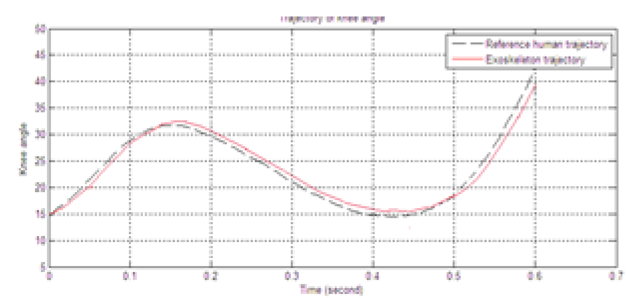

Fig 8. Trajectory of knee angle (degree)

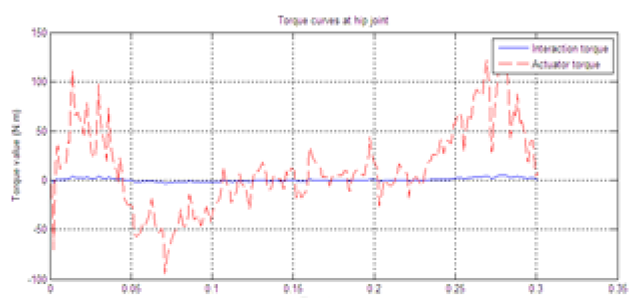

Fig 9. Interaction and actuator torques of hip joint

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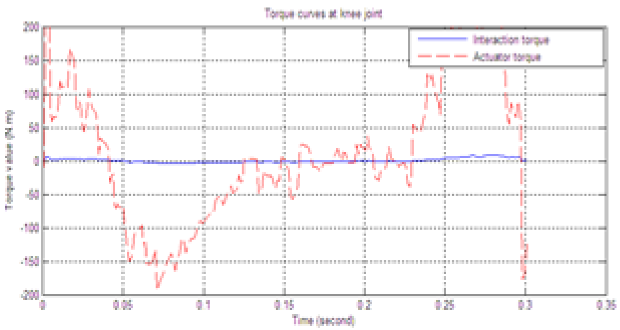

Fig 10. Interaction and actuator torques of knee joint

Figs 7, 8 show the position tracking trajectories of the exoskeleton to the human's motion at hip and knee joints in the stance phase which spends about 60% of one walking cycle. The tracking error is small. The exoskeleton is able to shadow the wearer's movements with small interaction torques represented in the Figs 9, 10. The two remain non-actuated DOFs at ankle and toe positions that are only controlled by the wearer are not shown in this simulation.

B. Virtual Torque Control Including PD Compensator for Swing Leg Model.

The swing leg phase is controlled by the control scheme as the Fig 11. For such control algorithm, the main ideal is to estimate the interaction torque that can be seen virtual torques, *e* vector describes these torques in the figure. The virtual torque values are estimated based on the deviation of the estimated overall torques and the actuator torques. The algorithm is based on the forward model of the exoskeleton $G'_{.exo}$. If G'_{exo} is perfect, $q_e/q_h \rightarrow 1$ and $T_{int} \rightarrow 0$. However, the uncertainty model error is one of major concerns for the control algorithms that based on model seriously. The estimated overall torques should be approached to those feed to the exoskeleton. In our approach, we suppose a PD compensator to implement our proposed approach. Although the $G'_{.exo}$ is estimated not perfectly, the estimated overall torques still approach to those feed to the exoskeleton system.

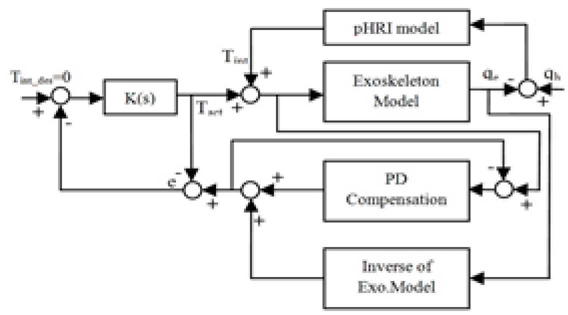

Fig 11. Virtual torque Control diagram using PD compensator applied to swing leg phase

The physical human robot interaction model (pHRI) is the same to equation (4). $K(s) = k_p + k_d.s$ is the gain function of estimated interaction torques. These parameters were identified by experimental work.

Figs 12, 13 and 14 show the simulation results of position tracking trajectories are very good at hip, knee and ankle joint. That means the swing leg is able to shadow the wearer's motions. The generated torque from the actuator is much larger in comparison with interaction torque from the wearer (Figs 15, 16). This means that the T_{act} from the actuator plays primary role to support or make main motion to move exoskeleton's thigh with very small effort. The interaction torques approach to zero values, this indicates that the wearer feels comfortably in walking although he/she wears a quite heavy exoskeleton.

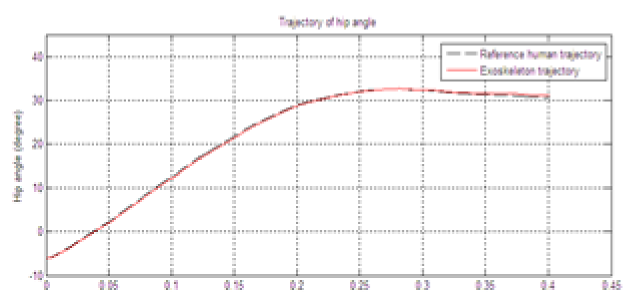

Fig 12. Trajectory of hip angle

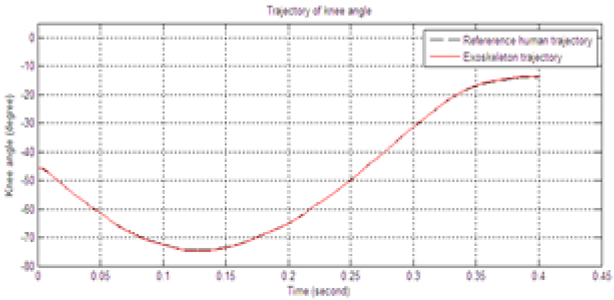

Fig 13. Trajectory of knee angle

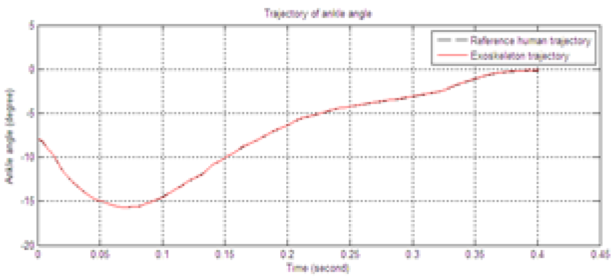

Fig 14. Trajectory of ankle angle

Fig 15. Interaction and actuator torques of hip joint

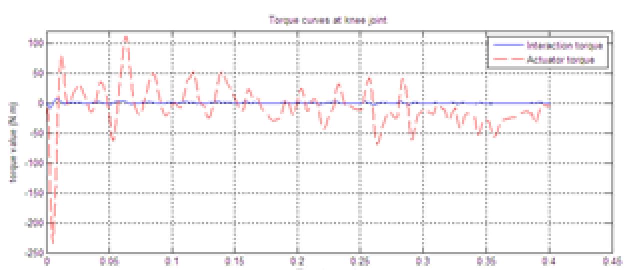

Fig 16. Interaction and actuator torques of knee joint

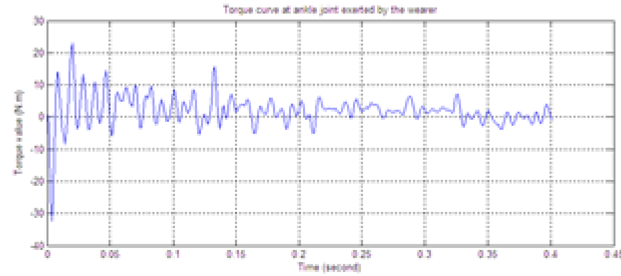

Fig 17. Interaction torque exerted by the wearer at ankle joint

The maximum torque value in the initial period of the motion cycle is reasonable because in this duration, the exoskeleton's thigh starts to move, the larger torque value is required from the actuator to overcome its inertia. The remaining non-actuated DOF at the ankle joint is only controlled by the wearer's foot. The torque curve is show in the Fig 17.

V. Conclusion And Future Work

This paper has presented briefly a lower extremity exoskeleton for human performance enhancement. Preliminary studies are mainly focused on dynamic model based on anthropomorphism, human-robot interaction induced dynamic model and hybrid control method applied two robot's legs. The proportional derivative compensation method is used to improve the control performance in case of unknown uncertainty model error in swing leg phase while the position control is used for the stance leg phase including gravity compensation. The obtained simulation results show the high feasibility of the proposed method applied to the real exoskeleton system that we are developing. The further works are focused on improvement of control algorithm that uses radial basis function neural network to compensate unknown uncertainty model error in the way that eliminates sensors at human robot interface. The physical human robot interaction model needs to implement further study based on learning model methods. In additional, cognitive human robot interaction will be studied to enhance performance of robot's operation which helps the robot respond to any human's motion. And finally, the development of the real system should be speeded up to make a benchmark for further studies in the future.

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REFERENCES

[1] M. Dollar and H. Herr, "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art" IEEE Transactions on Robotics, Vol.24, No.1, 2008

[2] K. Anama, Adel Ali Al-Jumailyb, "Active Exoskeleton Control Systems: State of the Art", International Symposium on Robotics and Intelligent Sensors, 2012 (IRIS 2012)

[3] W. Huo, S. Mohammed, J. C. Monero, and Y. Amirat, "Lower Limb Wearable Robots for Assistance and Rehabilitation: A State of the Art," *IEEE Systems Journal*, no. 99, pp. 1-14, 2015.

[4] C. Mendez, Y. Aoustin, and C. Rengifo, "Evaluation of the Aid Provided by an Exoskeleton in the Reduction of the Joint Torques Exerted by Human Lower Limbs: A Simulation Study," *Latin America Transactions, IEEE (Revista IEEE America Latina)*, vol.13 , no. 2 , pp. 428 – 433, 2015.

[5] D. Chen, M. Ning, B. Zhang, and G. Yang, "Control strategy of the lower-limb exoskeleton based on the EMG signal," *IEEE International Conference on Robotics and Biominmetrics (ROBIO)*, pp. 2416-2420, 2014.

[6] A.Tsukahara, Y. Hasegawa, and Y. Sankai, "Gait support for complete spinal cord injury patient by synchronized leg-swing with HAL", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2011.

[7] B.C. Tsai, W.W. Wang, L.C. Hsu, L.C. Fu, and J.S. Lai, "An articulated rehabilitation robot for upper limb physiotherapy and training," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),2010.

[8] S. Jezernik, G. Colombo, T. Keller, H. Frueh, and M. Morari, "Robotic orthosis Lokomat: a rehabilitation and research tool, Neuromodulation: Technology at the Neural Interface", vol. 6, no. 2, pp. 108-115, 2003.

[9] H.Kawamoto, Y. Sankai, "Comfortable Power Assist Control Method for Walking Aid by HAL-3", IEEE SMC, 2002.

[10] Y.Sankai, "HAL: Hybrid Assistive Limb based on Cybernics", Global COE Cybernics,System and Information Engineering, University of Tsukuba Tennodai, Tsukuba, Ibaraki, 305-8573, Japan.

[11] H. Kawamoto, Y.Sankai, "Power Assist Method Based on Phase Sequence Driven by Interaction between Human and Robot Suit", Proceedings of the 2004 IEEE International Workshop on Robot and Human Interactive Communication Kurashiki, Okayama Japan, September 20-22, 2004.

[12] H.Kazerooni, "Exoskeleton for Human Power Augmentation", IEEE/RSJ International Conference on intelligent Robots and Systems, 2005.

[13] A. Zoss, H.Kazerooni, "On the Mechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)", IEEE/RSJ International Conference on intelligent Robots and Systems, 2005.

[14] H. Kazerooni, A.Chu, R. Steger, "That Which Does Not Stabilize, Will Only Make Us Stronger", The International Journal of Robotics Research Vol. 26, No. 1, pp. 75-89, January 2007.

[15] H. Kazerooni, J.L.Racine, L.Huang, and R.Steger, "On the Control of the Berkeley Lower Extremity Exoskeleton (BLEEX)", Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, April 2005.

[16] H.Kazerooni, R.Steger, L.Huang, "Hybrid Control of the Berkeley Lower Extremity Exoskeleton (BLEEX)", International Journal of Robotics Research, Vol.25, No.5-6, pp.561-573, May-June 2006.

[17] Z.Yang, L.Gui, X.Yang, W.Gu, Y.Zhang, "Simulation Research of Exoskeleton Suit Based on Neural network Sensitivity Amplification Control", Proceedings of the IEEE International Conference on Automation and Logistics, Jinan, China, August 18 - 21, 2007.

[18] I. P. Herma, 2008, Physics of the Human Body, Springer.