2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)
August 19~22, 2016 at Sofitel Xian on Renmin Square, Xian, China

Design of the Omni Directional Treadmill Based on an Omni-Pulley Mechanism

Hosu Lee[1], Sanghun Pyo[1], Sangjoon Park[2] and Jungwon Yoon[3]
[1,3] Department of Mechanical Engineering, Gyeongsang National University, Jinju, 660-701, Korea
(Tel : +82-55-772-2576; E-mail: jwyoon@gnu.ac.kr)
[2] Electronics Telecommunications Research Institute, Daejeon, 305-700, Korea
(Tel : +82-42-860-5474; E-mail: sangjoon@etri.re.kr)

Abstract - In recent years, extensive research and development have been carried out for devices and software that interact with the virtual reality environment. Omni-directional treadmill (ODT) lies among such devices; it simulates a human locomotion such as walking and running. It provides a two-dimensional locomotion interface function for interacting an avatar in the virtual environment and the user in the real environment. Existing Omni-directional treadmills are heavy, complex and exhibit low power transmission efficiency. Their substantial drawback is limitation of rapid acceleration and deceleration, which make them inadequate for applications that require high acceleration and deceleration, such as training of soldiers in virtual environment. Therefore, this paper suggests a novel design of Omni-directional treadmill. Our proposed system is simpler, lightweight and produces a high power transmission efficiency based on the suggested Omni-pulley mechanism. Besides, we performed the dynamic analysis of our design using simulation program ADAMS® and calculated the drive power, and selected the required drive motor based on the results. Furthermore, we developed and drove a prototype of the designed system, and could discover a capability of system. The proposed device will be used as locomotion interface platform in various virtual reality environments such as training of soldiers, gaming/educational experiences and gait rehabilitation. Future task is implementation of the whole system based on suggested design.

Keywords – Omni directional treadmill, 2-dimensional treadmill, locomotion interface device.

1. Introduction

In recent years, extensive research and development have been carried out for devices and software that interact with the virtual reality and augmented reality etc. The Digi-Capital company, England investment bank, expects that the market relative to the virtual reality and augmented reality will rapidly grow from about 5 billion USD at 2016 to 150 billion USD at 2020 [1].

The user's involvement feel is important in virtual reality, so high functionality virtual reality interface device is needed for it [2],[3]. Among several existing virtual reality interface devices, omni-directional locomotion device can simulates a human locomotion such as walking and running and provides a two-dimensional locomotion interface function for interacting an avatar in the virtual environment and the user in the real environment, this provides a clear advantage for using ODT in rehabilitation besides existing devices [4-11]. As ODT's locomotion interface device give higher involvement feel more than joysticks or motion platforms, it can provide experience similar to real environment in virtual reality, and also induce user towards active participation. Thus, ODT can be efficiently used as a locomotion interface in several platforms, i.e. army training, game, education, architecture, rehabilitation etc. in virtual reality [12-16].

The omni-directional locomotion device can be divided into: a Standstill way to imitate walking by standstill and a Moving surface way to simulate only ground contact among walking action, and a Moving pedal way to simulate moving foot action generally. The Moving surface way is the most likely to give natural walking feel to user, and there are big sphere, tile, ball, treadmill etc. types among Moving surface way omni-directional locomotion devices. Hence, an omni-directional treadmill type can simulate moving and changing direction of real ground most naturally. Fig. 1 shows an omni-directional treadmill, it consists of segments which have independent belts each, it provides 2-dimension locomotion interface to user by making use of Y-axis movement as belt of unit segment, and of X-axis's infinite surface as rotation of whole segments like caterpillar.

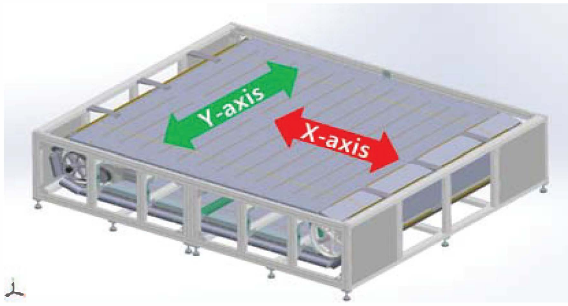


Fig. 1. Fast Omni Directional Treadmill (F-ODT)

Existing omni-directional treadmills are the U.S army research's ODT(Omni Directional Treadmill)[17], the Cyberwalk developed by Europe consortium[18], and the Torus Treadmill of University of Tsukuba in Japan[19]. Drive mechanism of the U.S.'s ODT is quite simple because Y-axis is driven by omni-wheel, but it has low

978-1-5090-0821-6/16/$31.00 ©2016 IEEE

power transmission efficiency because an omni-wheel transfers power by friction wheel way of line unit. On the other hand, Y-axis power transmission efficiency of the Cyberwalk is high because all segments are attached to hydraulic motors. But since weight of each segment is increased, a high power X-axis driving motor is needed. Lastly, the distance between segments of Torus treadmill is just 2 mm due to improved segments array arrangement; however it has a complex mechanism because actuators are attached to each segment, and surface is too narrow to perform soldier training. Thus, drawbacks of previously developed devices are low acceleration performance because of high weight and complexity and limitation of power transmission efficiency. So these devices can't provide environment of rapid changes or turning directions (acceleration is less than 1 m/s^2). Therefore it is unsatisfactory to apply these devices in virtual reality applications which require rapid changes of high acceleration like intensive soldier training programs.

For this reason, This paper proposes Fast Omni Treadmill(F-ODT) that can provide Y-axis motion in geared way, and X-axis motion uses light power transmission(high tension timing belt) and simplified assemble between segment and belt driven system. Therefore, as Y-axis motion achieves improved power transmission efficiency more than U.S. ODT and X-axis has lower inertia compared with the Cyberwalk, we expect that proposed system can have function of high acceleration.

In section 2, the mechanism and design of suggested device is explained. In section 3, we carried out dynamic analysis for validating kinematic and calculating desired motor power. And experiments of driving of the real implemented prototype are discussed in chapter 4, and conclusion in section 5 follows.

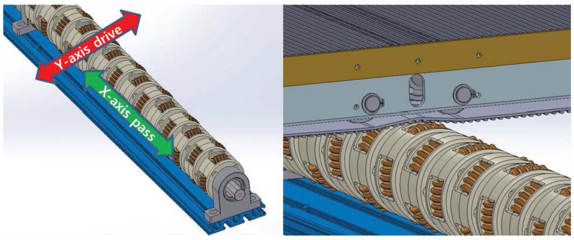
2. Mechanism & Design

Fig. 1 shows formation of developed the F-ODT (fast omni-directional treadmill). Total 64 segments make X-axis movement like the caterpillar, and each segment which has independent belt makes Y-axis movement. In addition, two vectors generated by this device are controlled to always place the user on the center, the user who has 2-dimensional DOF(degree of freedom) can move like on a real ground.

2.1 Y & X-axis driving mechanism

Y-axis driving mechanism is shown in Fig. 2. Since power is transferred through gear which is coupled between the omni-pulley (designed in this paper) and belt surface of segment shaped tooth, Y-axis system has high power transmission efficiency. Omni-pulleys which are made up roller shaped teeth allow segments to pass through the X-axis, it can transmit power in the Y-axis as the same time(see Fig. 2(a)). Therefore efficiency is higher than power transmission of line friction in the U.S. ODT, and system is lightweight because each segment does not contain actuators unlike the Cyberwalk.

Likewise, X-axis power is transferred by connecting segments and rib (bump) of X-axis driving timing belt by pins [Fig. 3]. Using this direct fastening method, instead of complex mechanical fastening such as roller, cam, chain etc., also using lightweight and high tensile timing belt to drive X-axis, system is expected to be simple and lightweight to reduce the noise.



(a) Array of omni-pulley (b) Driving mechanism

Fig. 2. Y-axis driving Mechanism

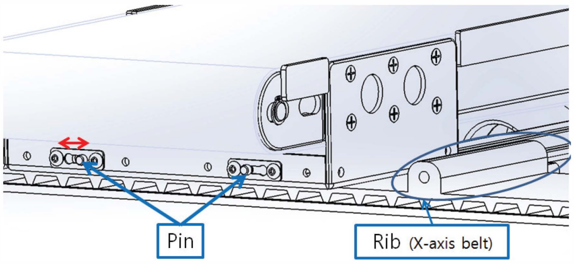


Fig. 3. X-axis assemble Mechanism

2.2 Driving system

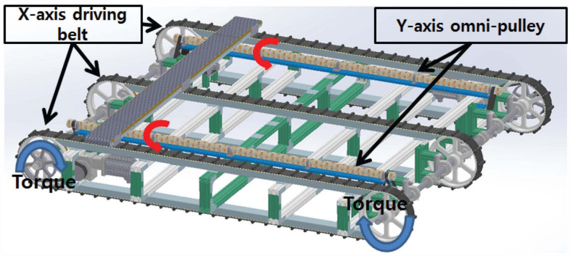


Fig. 4. Driving mechanism for F-ODT

As shown in Fig. 4, Y-axis motion is driven by two omni-pulley arrays. Moreover they are driven by corresponding servo motors, and these two motors are synchronized for operation.

A total of three timing belts drive segments on X-axis. Each timing belt is made of high tensile polyurethane material and have many ribs (bump) which can be fastened to the segments as shown Fig. 4. When power generated from motor is transferred to driving pulley, it makes X-axis motion by driving 64 segments like caterpillar. X-axis is also driven by two servo motor synchronized for operation.

2.3 Unit segment

Fig. 5 shows a unit segment which has polyurethane material having teeth surface, tensioner, bearing, assemble part, guide roller, frame etc. and is an independent treadmill. Function of Bearing and guide roller is to make and maintain contact force between belt and omni-pulley.

Belt is designed in a shape of common use timing belt turned inside out. Considered T-type timing belt has strong wear resistance and can be efficiently used in flexible environments because of built-in core wire of steel code. It is important to determine small enough pitch not to give sense of difference at user's foot, whereas it also needs to be large enough for big tangential force from teeth. So we choose T5, T10 among T2.5, T5, T10, T20 pitch number. As we have selected commonly used timing belt, we can reduce time and money for design.

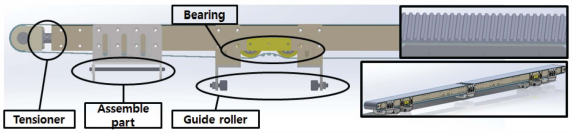


Fig. 5. The unit segment

2.4 Omni-pulley

Shape of omni-pulley is designed according to teeth of timing belt T5, T10 (see Fig. 6 (a) (b)), and material is chosen to be Al 6063. The detailed configuration is mentioned in Table 1. We can get tangential force (turning force) generated at teeth of omni-pulley from equation (1), W. Lewis design equation modified by C.G.Barth[20].

$$F_t = f_v \cdot f_w \cdot \sigma_b \cdot p \cdot b \cdot y \qquad (1)$$

where f_v is speed factor, f_w is load factor, σ_b is allowable bending stress, p is pitch, b is face width, and y is tooth factor by pitch.

$$F_t = f_v \cdot k \cdot m \cdot b \cdot \frac{2Z_1Z_2}{(Z_1+Z_2)} \qquad (2)$$

Also, we can obtain from E. Videky's gear contact stress equation (2). m is module, Z is the number of tooth, k is stress intensity factor and is defined equation (3).

$$k = \frac{\pi}{8}\sigma_c^2 \sin(2\alpha)\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right) \qquad (3)$$

Where, σ_c is allowable compressive stress, α is pressure angle, ν is poisson's ratio, and E is Young's modulus. Properties and factors of designed omni-pulleys are same, but only configuration is different among the two versions designed. Using above mentioned equations, we can get tangential force ratio of omni-pulley Ver.1 and Ver.2 by substituting configuration value different from each other and we got 1:3.7 from equation (1), 1:2.5 from equation (2). Thus because tangential force of Ver. 2 can be generated 2.5 or 3.7 times more than Ver. 1, we choose Ver. 2 model and made real prototype, and belt of T10 pitch number is used for segments.

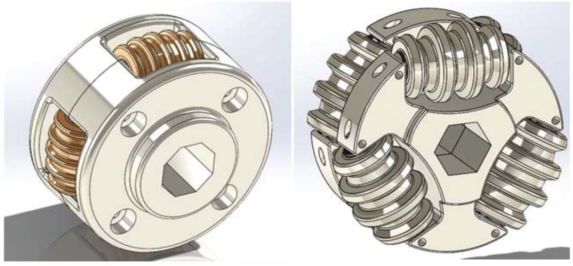

(a) Ver. 1 (p = 5) (b) Ver. 2 (p = 10)
Fig. 6. The omni-pulley

Table 1 The parameters of the omni-pulley

	Whole depth	Face width	Pitch	Pitch circle diameter	No. of teeth
Ver. 1	1.45 mm	2 mm	5 mm	61.8 mm	20 EA
Ver. 2	3.2 mm	4.3 mm	10 mm	72 mm	12 EA

3. Dynamics analysis

3.1 X & Y-axis dynamics analysis

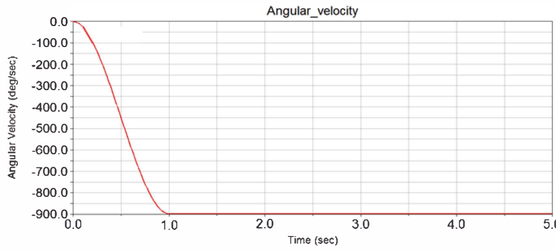
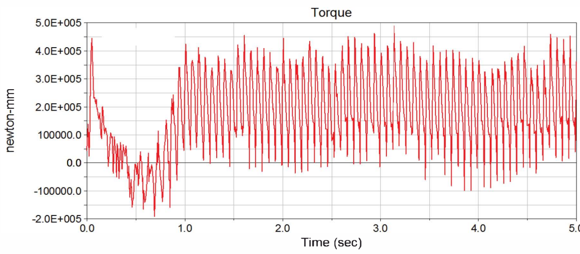
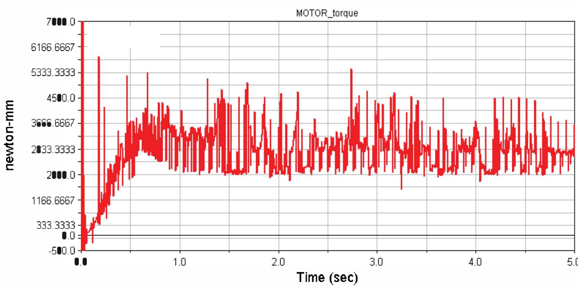


Fig. 7. Input angular vel.



(a) X-axis output torque



(b) Y-axis output torque

Fig. 8. Desired driving torque of X and Y-axis

For dynamics analysis of the suggested device the commonly used multibody dynamics analysis program ADAMS® is used in this paper. We gave proper joints, conditions, and supposed no power loss from motor to driving pulley except for friction. Initial tensile of timing belt of X & Y-axis is given appropriate value by considering belt configuration (7). Similarly giving angular velocity at X-axis driving pulley and Y-axis omni-pulley, we carried out dynamics analysis for torque output required at driving pulley and velocity segment. Input angular velocity of driving pulley is detemineed form equation (4).

$$v = r\theta \quad (4)$$

Here, r is radius of X & Y-axis pulley, and according to target velocity $3\mathrm{m/s}$ and radius of pulley, we can get the input angular velocity θ. And also as shown in Fig. 7, Input angular velocity can satisfied target acceleration ($3\mathrm{m/s^2}$) by using STEP function in ADAMS.

Fig. 8 shows output torque graph of X & Y-axis, which is the desired driving torque for the system. As shown in Table 2, we represent maximum and average torque and calculate real desired motor toque to apply designed gear ratio. The capacity of motor is calculated by equation (5).

$$P = T\omega \quad (5)$$

This required torque of Y-axis is the value needed to drive only one segment, and Omni pulleys have to drive total 11 segments, so each motor must support drive of 5.5 segments. Thus real desired torque for each motor of Y-axis is 5.5 times of output torque of Y-axis.

Table 2. Desired torque, capacity of motor

	A. Torque (pulley)	B. Torque (motor)	C. Angular velocity (pulley)	Capacity of motor (A × C)
X-axis	(max)489 Nm	48.9 Nm	15.63 rad/s	7.6 kW
X-axis	(avg.)179 Nm	17.9 Nm	15.63 rad/s	3 kW
Y-axis	(max)32.23Nm	21.49 Nm	92.31 rad/s	2 kW
Y-axis	(avg.)16.5 Nm	11 Nm	92.31 rad/s	1 kW

3.2 Motors select

Table 3. Specification of decided motor

	Rated output	Rated torque	Instantaneous peak torque	Rated speed
SGMG V-44A	4.4 kW	28.4 Nm	71.1 Nm	1500rpm
SGMG V-20A	1.8 kW	11.5 Nm	28.7 Nm	1500rpm

According to result of analysis, Servo motors SGMGV-44A(X-axis) and SGMGV-20A(Y-axis) manufactured by Yaskawa® are selected. Since servo motor can undertake about 3 times from rated torque to instantaneous peak torque, so we choose motors whose instantaneous peak torque satisfies desired maximum torque value and rated output of them satisfies calculated capacity of motor.

4. System driving

4.1 System low-level control

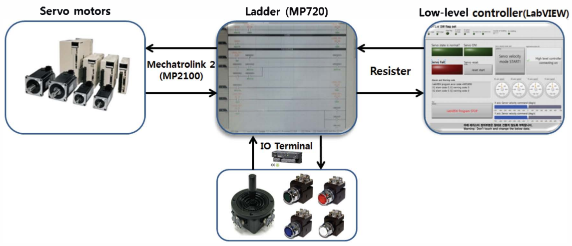


Fig. 9. Diagram of low control of system

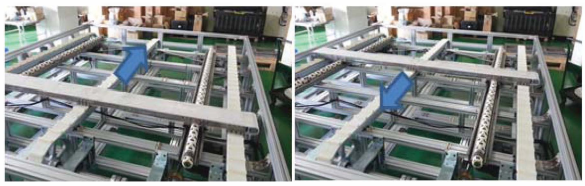
We built a low-level controller for motor synchronization and control of outside I/O values call, alarm watch, reset, and velocity input etc. by LabVIEW®. As shown in Fig. 9, LabVIEW® accesses the register values of MP720(Ladder program), and MP720 communicates with MP2100, motion controller of PCI type by using Mechatrolink2. At this time, outside I/O is connected with MP720, and LabVIEW® can control outside I/O. And motors of each axis are synchronized by MP720.

4.2 Drive test

For validation of suggested system, we made prototype assembled two segments, based on designed materials. And also we test single axis driving and simultaneous driving of X & Y axis [see Fig. 10]. Various input velocity commands are shown in Table 4. As a driving test result, we confirmed that there was no problem qualitatively; also we measured surface velocity at Y-axis during single axis driving by tachometer (LANDTEK, DT-2236) for quantitative data analysis. Average velocity is measured to be 1.97 m/s, hence the power transmission efficiency is 98.5 % (see Fig. 11)

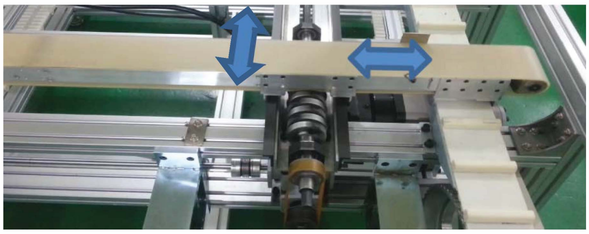
Table 4. Driving input velocities of the system

	Input velocity	Max acceleration
X-axis	- 2 m/s - 3 m/s - $1.5\sin(3.14t)\ m/s$	$4.71\ \mathrm{m/s^2}$
Y-axis	- 2 m/s - 3 m/s - $1.5\sin(3.14t)\ m/s$	$4.71\ \mathrm{m/s^2}$
X & Y-axis	X : $0.16\sin(3.14t)\ m/s$ Y : $\sin(5t)\ m/s$	$0.5\ \mathrm{m/s^2}$ $5\ \mathrm{m/s^2}$



(a) X-axis drive (2 m/s)

(b) Y-axis drive ($1.5\mathrm{m/s}$, $4.7\mathrm{m/s^2}$)



(c) X&Y-axis drive

(X : 0.16 m/s , 0.5 m/s^2, Y : 1 m/s , 5 m/s^2)

Fig. 10. Snapshots of driving of system

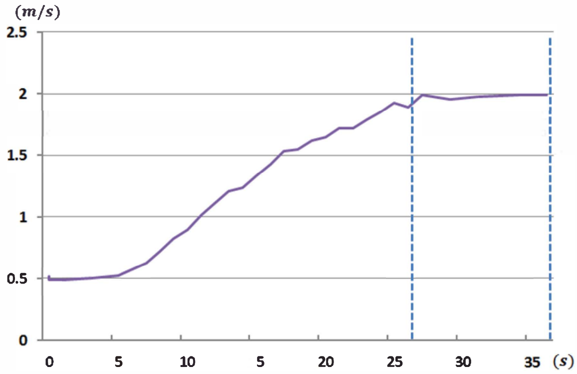


Fig. 11. Measurement of velocity of Y-axis

5. Conclusion

Market of Virtual reality and augmented reality is expected to increase to 150 billion USD by the year 2020. Omni-directional locomotion device makes possible the interfacing of space sense by locomotion actions, unlike conventional virtual reality interface devices which provided only vision or tactile. Therefore, it can be used in new locomotion interface devices to apply exercises of the virtual environment, such as military training, games and gait rehabilitation.

Unlike the existing devices having the disadvantages of the acceleration performance limit due to heavy, complex system and the limitation of the power transmission efficiency, the F-ODT proposed in this paper avoids using complex mechanical elements such as roller, cam, chains, and uses a light-weight, high-strength timing belts for driving X-axis. As a result, it was able to more easily configure a fastening system of the segments, and the system could be configured to a light device compared with the conventional mechanical components for power transmission. Also it is designed to be a high acceleration system by increasing the Y-axis driving transmission efficiency due to toothed coupling between the omni-pulley and the segment. Lastly the parts (bracket, beam, pulley, belt, spindle etc.) made up proposed device is designed, so it means that it is easy to supply part because of no need to manufacture materials, and to reduce cost. Thus advantages of system are good maintainability and cheap.

This paper proposed F-ODT and determined the motors for device by using dynamics simulation of ADAMS and described the built low controller, and presented the prototype of system. Also, we tested and measured for validation, and then confirmed the possibility of system.

In the future, according to materials of our verified and designed device, we will make the whole device. Then we want to build omni-directional interface system integrating virtual reality environment.

Acknowledgement

This work was supported by the Civil-Military Technology[14-CM-MC-15] and the National Research Foundation Korea (NRF) (BK21 PLUS)

References

[1] Digi-Capital, Augmented/Virtual Reality to hit $150 billion disrupting mobile by 2020, http://www.digi-capital.com/news/2015/04/augmentedvirtual-reality-to-hit-150-billion-disrupting-mobile-by-2020/#.VTSQc01WGBY.

[2] J.-W. Yoon, J.-W. Park, and J.-H. Ryu, "Intelligent Control of a Virtual Walking Machine for Virtual Reality Interface," *Journal of Institute of Control, Robotics and Systems*, vol. 10, no. 11, pp. 926-934, 2006.

[3] J. Yoon, J. Ryu, "A novel locomotion interface with two 6-dof parallel manipulators that allows human walking on various virtual terrains", *The International Journal of Robotics Research*, vol. 25, no. 7, pp. 689-708, 2006.

[4] S. H. Pyo, M. G. Oh, and J. W. Yoon, "Development of an active haptic cane for gait rehabilitation," in 2015 IEEE International Conference on Robotics and Automation (ICRA), May 2015, pp. 4464–4469.

[5] M. R. Afzal, M.-K. Oh, C.-H. Lee, Y. S. Park, and J. Yoon, "A portable gait asymmetry rehabilitation system for individuals with stroke using a vibrotactile feedback," *BioMed Research International*, vol. 2015, pp. 1–16, 2015. [Online]. Available: http://dx.doi.org/10. 1155/2015/375638

[6] S. Pyo, J. Yoon, and M.-K. Oh, "A novel robotic knee device with stance control and its kinematic weight optimization for rehabilitation," *Robotica*, vol. 32, no. 08, pp. 1245–1263, jun 2014.

[7] M. R. Afzal, H.-Y. Byun, M.-K. Oh, and J. Yoon, "Effects of kinesthetic haptic feedback on standing stability of young healthy subjects and stroke patients," *Journal of NeuroEngineering and Rehabilitation*, vol. 12, no. 1, p. 27, 2015. Available: http://dx.doi.org/ 10.1186/s12984-015-0020-x

[8] M. R. Afzal, M.-K. Oh, H. Y. Choi, and J. Yoon, "A novel balance training system using multimodal biofeedback," *BioMedical Engineering OnLine*, vol. 15, no. 1, apr 2016. Available: http://dx.doi.org/ 10.1186/s12938-016-0160-7

[9] J. Yoon, B. Novandy, C.-H. Yoon, and K.-J. Park, "A 6-DOF gait rehabilitation robot with upper and lower limb connections that allows walking velocity updates on various terrains," *IEEE/ASME Transactions on Mechatronics*, vol. 15, no. 2, pp.

201–215, apr 2010. [Online]. Available: http://dx.doi.org/10.1109/ tmech.2010.2040834

[10] S. Gharatappeh, G. Abbasnejad, J. Yoon, and H. Lee, “Control of cable-driven parallel robot for gait rehabilitation,” in 2015 12th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI). Institute of Electrical & Electronics Engineers (IEEE), oct 2015.

[11] G. Abbasnejad, J. Yoon, and H. Lee, “Optimum kinematic design of a planar cable-driven parallel robot with wrench-closure gait trajectory,” *Mechanism and Machine Theory*, vol. 99, pp. 1–18, may 2016. [Online]. Available: http://dx.doi.org/10.1016/j.mechmachtheory.2015.12.009

[12] I. Frissen, et al. "Enabling unconstrained omnidirectional walking through virtual environments: an overview of the CyberWalk project," Human Walking in Virtual Environments. Springer New York, 2013. pp. 113-144.

[13] J.L. Souman, et al. "CyberWalk: Enabling unconstrained omnidirectional walking through virtual environments," *ACM Transactions on Applied Perception*, vol. 8, no. 4, pp.25, 2011.

[14] A.R. Ruddle, E. Volkova, and H.H. Bülthoff. "Walking improves your cognitive map in environments that are large-scale and large in extent," *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 18, no.2, pp.10, 2011.

[15] A.A. Khan, O. Naseer, D. Iliescu, E. Hines, “Fuzzy Controller Design for Assisted Omni-Directional Treadmill Therapy”, *The International Journal of Soft Computing and Software Engineering*, Vol. 3, No. 3, pp. 30-37, 2013.

[16] M.-H. Cha, S.-H. Han, and Y.-C. Huh, “A Walking Movement System for Virtual Reality Navigation,” *Transactions of the Society of CAD/CAM Engineers*, vol. 18, no. 4, pp. 290-298, 2013.

[17] A. C. Boynton, K.L. Kehring, and T.L. White, “Biomechanical and Physiological Validation of the Omni-Directional Treadmill Upgrade as a Mobility Platform for Immersive Environments”, No. ARL-TR-5510, Army Research Lab Aberdeen Proving Ground MD, 2011.

[18] M. Schwaiger, T. Thuimmel, H. Ulbrich, “Cyberwalk: An advanced prototype of a belt array platform," IEEE International Workshop on Haptic Audio Visual Environmants and Games, pp. 50-55, 2007.

[19] H. Iwata, “The Torus Treadmill: Realizing Locomotion in VEs,” *Computer Graphics and Applications, IEEE*, vol. 19, pp. 30-35, 1999.

[20] J. P. Hong, Mechanical design, Theory and Practice, Ver. 5, Kyobo Book, 2012.