Effects of knee alignment on human gait based on wireless sensors

Norihiko Saga*, Saeko Irie, Yasutaka Nakanishi, Hiroki Dobashi and Akitoshi Sogabe

Department of Human System Interaction,
Kwansei Gakuin University,
2-1 Gakuen, Sanda, Hyogo, Japan
E-mail: saga@kwansei.ac.jp
E-mail: s_irie324@opal.ocn.ne.jp
E-mail: crg80061@kwansei.ac.jp
E-mail: dobashi@fc.ritsumei.ac.jp
E-mail: sogabe@konan-u.ac.jp
*Corresponding author

Abstract: This study has been conducted to measure human gait locomotion according to different lower extremity alignments, and to assess the alignment effects on knees and leg muscles. Subjects were separated into three groups by knee alignment as normal knee, genu varum, and genu valgum. We conducted a synchronisation experiment using motion capture, tactile sensor and muscle potential in order to investigate the effect of the muscle activity due to differences in the alignment of the knee, and we are considering the difference in the motion analysis during walking, ground reaction and EMG. The results, were differences in the EMG and walking motion by knee types.

Keywords: biomechanics; walking; knee alignment; human gait.

Reference to this paper should be made as follows: Saga, N., Irie, S., Nakanishi, Y., Dobashi, H. and Sogabe, A. (2013) 'Effects of knee alignment on human gait based on wireless sensors', *Int. J. Biomechatronics and Biomedical Robotics*, Vol. 2, Nos. 2/3/4, pp.118–123.

Biographical notes: Norihiko Saga is a Professor in the Department of Human System Interaction at Kwansei Gakuin University of Japan. He received his PhD in Mechanical Engineering from Shinshu University. His current research interests are biorobotics, assistive technology for human and sports engineering.

Saeko Irie received her BEng in Informatics from Kwansei Gakuin University in 2013.

Yasutaka Nakanishi is a student from Kwansei Gakuin University in Human System Interaction.

Hiroki Dobashi is an Assistant Professor in the Department of Robotics at Ritsumeikan University of Japan. He received his PhD in Mechanical Engineering from Kyoto University. His current research interests are factory automation.

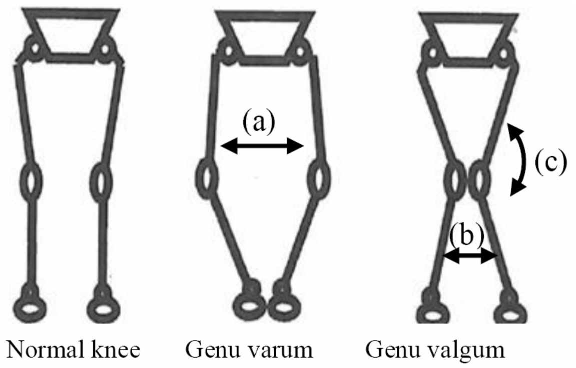
Akitoshi Sogabe is an Associate Professor in the Department of Education and Research Centre at Konan University of Japan. He received his PhD in Sports Medicine from Tsukuba University. His current research interests are sports science and biomechanics.

This paper is a revised and expanded version of a paper entitled 'Influence of lower extremity alignment on human gait based on wireless sensors' presented at the International Conference in Mechatronics and Machine Vision in Practice (M2VIP), M2VIP 2012, Auckland, 28–30 November 2012.

1 Introduction

In recent years, development of walking support equipment and rehabilitation equipment has been promoted extensively for people with disabilities, those with knee trouble (Yamawaki et al., 2012; Sawicki et al., 2006; Doorenbosch and Harlaar, 2003), and elderly people. A dynamic model was produced to support this effort. Results show the joint moment that is generated when a person who needs such equipment performs various exercises. The load applied to the knee can be estimated from measurements of the floor reaction force and from motion analysis. For a musculoskeletal model produced based on results of muscle activity measurement, walking behaviours can be simulated to check the walking activity of elderly people with less knee load. Thereby, effects of wearing walking support equipment can be evaluated. Although muscle activity and muscle mass (Sogabe et al., 2009; Mohamed et al., 2002) are reported as dependent on different knee alignments found for normal knee, genu varum, and genu valgum configurations such as those shown in Figure 1, no study of respective knee joint alignments or assessment of walking activity to reduce burdens on muscles has beenreported. This study was undertaken for construction of a walking model for each knee alignment (normal knee, genu varum, and genu valgum) for walking activities on a treadmill. In addition, the floor reaction force and muscle activity were measured in synchronisation with video pictures using four CCD cameras. This report describes results measured using multimodal sensors to ascertain the influence on walking activity according to differences of lower extremity alignment.

Figure 1 Knee alignments of three types



2 Subject

We performed a gait analysis with 18 subjects. They are healthy men in their 20 s. The physical characteristics of the subjects are summarised in Table 1. Subjects were excluded from the study if they had a history of knee pain or pathology. In this study, subjects were divided into three groups (normal knee, genu varum, and genu valgum) considering

a intercondylar (IC) distance of the knee

b intermalleolar (IM) distance

c femorotibial angle (FTA),as shown in Figure 1.

FTA ≥ 173°and <178° was considered as normal knee, FTA ≥ 178° and IC distance ≥3 cm was considered as genu varum, and FTA < 173°and IM distance ≥3 cm was considered as genu valgum.

3 Motion

3.1 Measurement and analysis methods

Figure 2 shows the motion capture system used for measuring walking activities. Four CCD cameras were installed and synchronised using a synchronous signal generator. Subjects were nine adult males in their 20 s with no trouble in the lower leg. They were classified as groups of three males each having normal knee, genu varum, and genu valgum lower leg configurations. The subjects walked with markers on the top of the head, and on both acromia, elbow joints, hand joints, pelvis, greater trochanters, knee joints, ankle joints, and toes, while the walking pace was set to 4.8 km/h. Walking was performed on a treadmill. The range of calibration was set appropriately. The pathway was recorded using cameras, which caught light reflections from the reflection markers illuminated by the light. Cameras were synchronised using a synchronous signal generator. Photographic images were recorded using a personal computer via a camera adapter with sampling frequency of 30 Hz. Regarding analysis, the photographed images were binarised using motion analysis software (Move-tr/32; Library Inc.) with constant luminance. Reflected light from the markers was recorded, showing three-dimensional coordinates.

Motion analysis specifically addressed the position coordinates of knee joints from touching of the heel of the right leg until leaving of the toe of the left leg.

3.2 Results of motion analysis

Figure 3 presents, looking from the front, the trajectories of the knee markers of subjects respectively having normal knee, genu varum, and genu valgum. The trajectory viewed from the front reveals that the normal knee motion progresses linearly in up–down directions to the walking direction, the genu varum motion tends to extend downward, and the genu valgum tends to move as if drawing an ellipse. Regarded comprehensively, of the legs of three types, the genu valgum motion apparently includes the most complicated knee movements.

Table 1 Physical characteristics of the subjects

Knee type	*Age*	*Hight (cm)*	*Weght (kg)*	*IC IM (cm)*	*FTA*
Nomal knee	22.2 ± 4.1	169.8 ± 4.2	77.1 ± 5.2	1.0 ± 1.2	175.8 ± 1.2
Genu varum	21.3 ± 2.3	171.0 ± 5.5	75.4 ± 8.3	5.1 ± 0.8	179.0 ± 0.9
Genu valgum	22.8 ± 3.9	169.8 ± 4.2	88.9 ± 21.1	5.6 ± 2.2	172.5 ± 0.5

Figure 2 Experimental set-up using wireless sensors (see online version for colours)

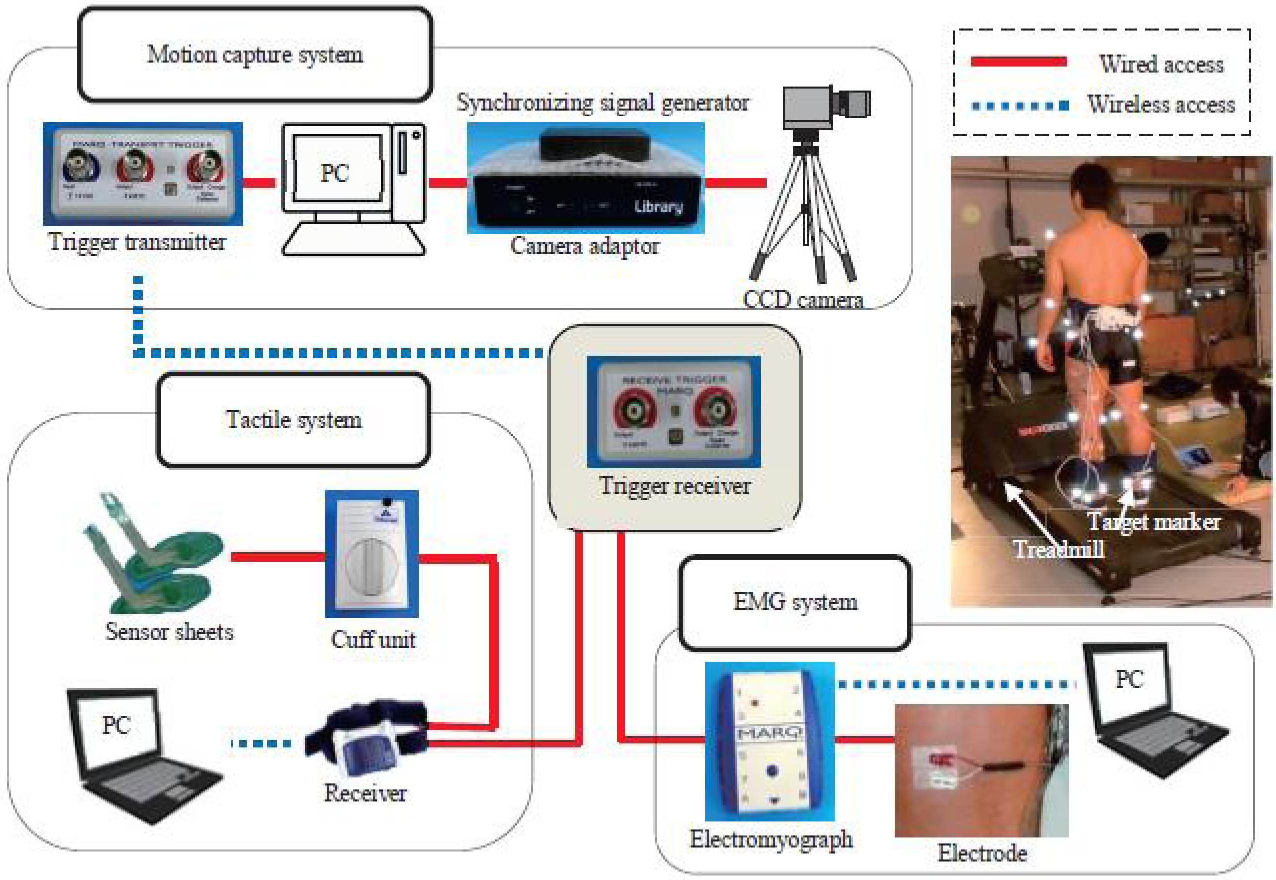
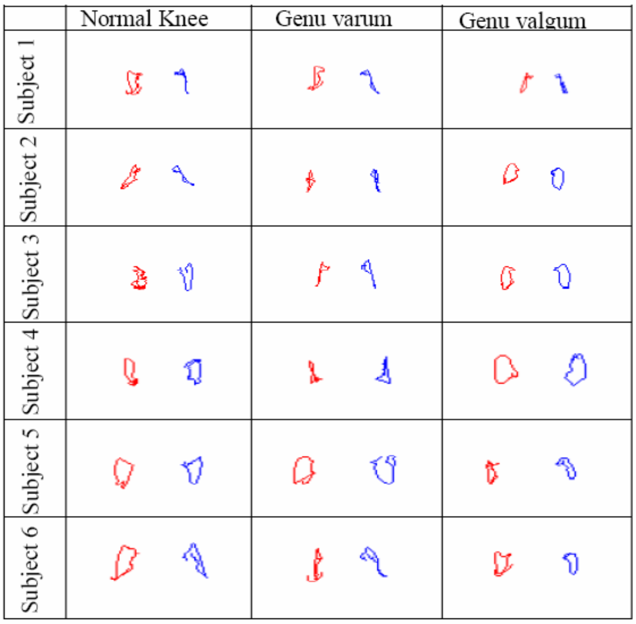


Figure 3 Trajectories of knee markers from the front (see online version for colours)



4 Measurements of the floor reaction force

4.1 Measurement methods

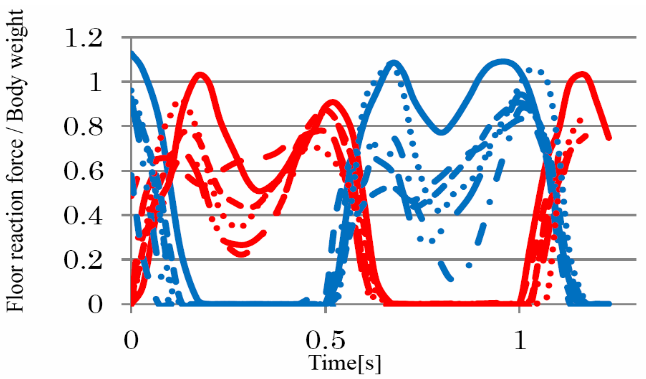
A tactile sensor was used for measurements of the floor reaction force in a vertical direction at the stance phase when walking. This measurement system using the tactile sensor consists of a sensor sheet, a cuff unit that relays pressure information from the sensor, a receiver that processes signals transmitted from the cuff unit and stores the data, and a computer, whereas wired or wireless connection might be used between the computer and receiver. At measurement, floor reaction forces were taken into the computer with sampling frequency of 40 Hz. They were processed using analysis software (F-Scan mobile; Nitta Corp.).

The sensor sheet was attached to the sock lining of shoes used by the subjects. Shoes with a simple profile and a flat sole were used to eliminate the influences of functions of shoes on the muscles and joints. Walking and motion analysis were synchronised.

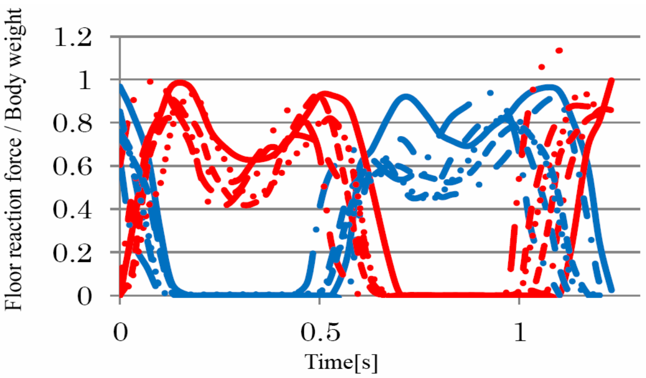
4.2 Results from tactile sensors

The measured floor reaction forces in vertical direction are presented in Figure 4. The pressure distribution at the feet bottom is depicted in Figure 3. These data were normalised by body weight. The floor reaction force level measured after touching of the right leg heel until leaving of toe of the left leg at walking is shown as a solid line for the right leg and as a broken line for the left leg.

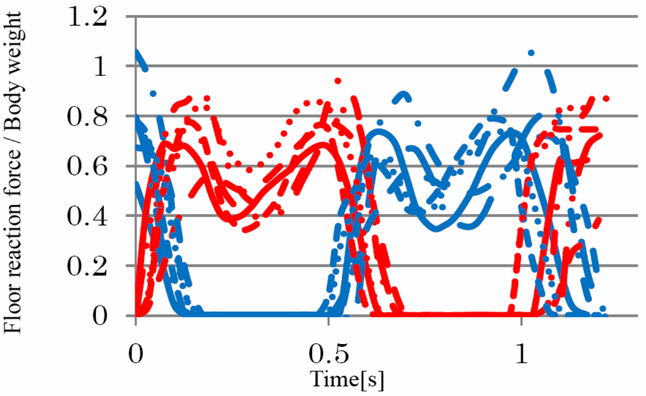
Figure 4 Floor reaction force in the vertical direction, (a) normal knee (b) genu varum (c) genu valgum (see online version for colours)



(a)



(b)



(c)

Although a slight difference of waveform is apparent for the floor reaction force, no significant difference was found for the alignment. Portions showing an extreme value observed in each graph are points where the heel touched and a point where kicking was made immediately before leaving of the toe. For the genu varum group, no difference was found for the floor reaction force around heel-touching and toe-leaving, although a difference was found with the normal knee and genu valgum. This difference suggests that with the normal knee and genu valgum, the floor is pressed strongly at kicking immediately before leaving of the toe, as compared to genu varum.

5 Measurement of muscle activity

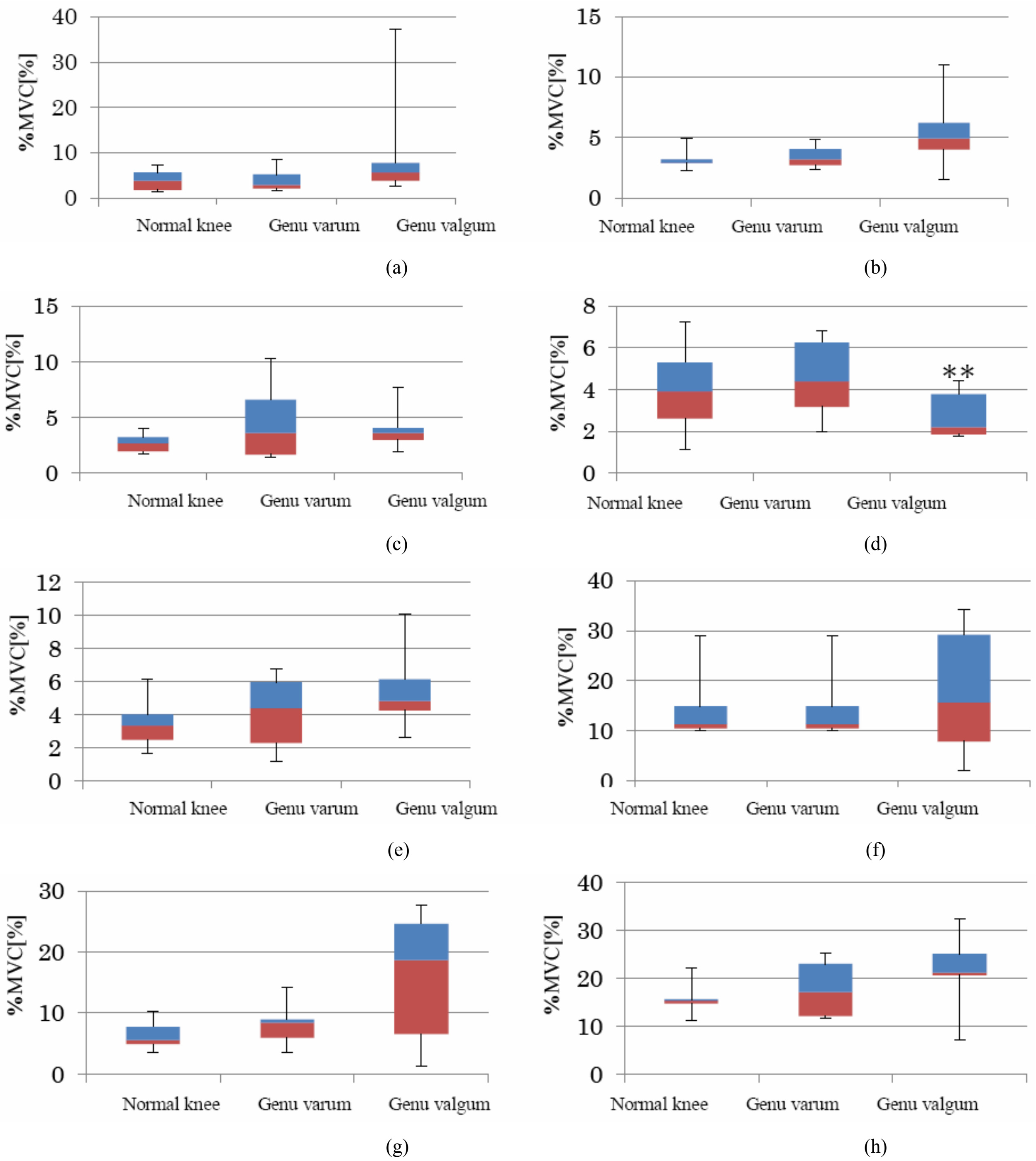
5.1 Measurement methods

Electromyography (EMG) data were obtained using muscle potential for eight locations (vastus medialis, vastus lateralis, biceps femoris, gastrocnemius medialis, gastrocnemius lateralis, rectus femoris, adductor longus, and tibialis anterior) of the lower extremity at walking activity. Furthermore, a maximum level of electromyograph was measured for an activity by which each muscle developed the maximum muscle force. An electrode was pasted on the skin surface as close to the target muscle as possible. It was then connected to a transmitter that was wearable by the body using an analogue amplifier. The transmitter was connected to a personal computer for data collection in a wireless fashion to enable recording of the muscle potential.

5.2 Results of electromyography

Data for about 2 s, corresponding to one cycle of walking, were analysed. The output was converted to rectified waveforms. The ratio of output for walking muscle activity of each knee type was measured against the maximum value of muscle potential at each muscle, as shown in Figure 5. The horizontal axis of the graph represents the type of normal knee, genu varum, or genu valgum. The vertical axis represents the distribution of the muscle potential level divided by the maximum measurement of that muscle in each walking activity by three alignment types. Furthermore, box plots of the graph show differences between numerical data of three alignment types through their five-number summaries: the smallest observation, lower quartile, median, upper quartile, and largest observation.

Figure 5 Ratio of muscle activity during walking and the maximum muscle potential in each type, (a) vastus mdialis (b) vastus lateralis (c) rectus femoris (d) adductor longus (e) biceps femoris (f) medial gastrocnemius (g) lateral gastrocnemius (h) tibialis anterior (see online version for colours)



Note: $**p < 0.001$.

For the vastus medialis, vastus lateralis, gastrocnemius medialis, adductor longus, and tibialis anterior of extensor muscle group, a great difference was noticed with waveforms depending on the type of alignment. With genu valgum, it is known that the vastus medialis, vastus lateralis, and tibialis anterior, develops a greater muscle force. With the normal knee and genu varum, output in the gastrocnemius medialis of flexor muscle group and the adductor longus outside engendered a large value. Moreover, there was a strong correlation between genu valgum group and the adductor longus (r = 0.931, p = 0.007).

6 Conclusions

In this study, subjects were classified by knee alignment: normal knee, genu varum, and genu valgum. Then motion analyses were conducted. The floor reaction force and muscle potential were measured. The obtained motion graphs revealed great differences, but no significant difference was found for the floor reaction force. Assessment of the muscle potential revealed that the activity site differed among knee alignments. Future studies will provide more data from different subjects and will reveal characteristics of the respective knee alignment types. From the obtained data, we expect to calculate the knee joint moment. Moreover, we plan to produce a musculoskeletal model, perform simulations of walking activity, and establish a design method for the development of medical and welfare equipment, while conducting comparisons with the actual activity of the muscle and actual measured values of the floor reaction force.

References

Doorenbosch, C.A.M. and Harlaar, J. (2003) 'A clinically applicable EMG-force model to quantify active stabilization of the knee after a lesion of the anterior cruciate ligament', *Clinical Biomechanics*, February, Vol. 18, No. 2, pp.142–149(8).

Mohamed, O., Perry, J. and Hislop, H. (2002) 'Relationship between wire EMG activity, muscle length, and torque of the hamstrings', *Clinical Biomechanics*, January, Vol. 17, Issue 8, pp.569–579.

Sawicki, G.S., Domingo, A. and Ferris, D.P. (2006) 'The effects of powered ankle-foot orthoses on joint kinematics and muscle activation during walking in individuals with incomplete spinal cord injury', *Journal of Neuro Engineering and Rehabilitation*, Vol. 3, No. 1, Article 3, pp.1–17, doi: 10.1186/1743-0003-3-3.

Sogabe, A., Mukai, N., Miyakawa, S., Mesaki, N., Maeda, K., Yamamoto, T., Gallagher, P.M., Schrager, M. and Fry, A.C. (2009) 'Influence of knee alignment on quadriceps cross-sectional area', *Journal of Biomechanics*, Vol. 42, No. 14, pp.2313–2317.

Yamawaki, K., Ariyasu, R., Kubota, S., Kawamoto, H., Nakata, Y., Sankai, Y., Eguchi, K. and Ochiai, N. (2012) *Application of Robot Suit HAL to Gait Rehabilitation of Stroke Patients: A Case Study*, Lecture Notes in Computer Science, Springer, Vol. 7383, pp.184–187.