

# Development of Variable Stiffness Gel Spats for Walking Assistance

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**Abstract**— In a previous study we developed an expansion and contraction actuator using PVC gel. We investigated the characteristics of the PVC gel actuator and found that its stiffness changed noticeably with a variation in the applied DC field. In this study, we designed new variable stiffness spats for walking assistance by incorporating the variable stiffness PVC gel actuator in generally used spats. The stiffness of the spats can be varied with the on and off switching of an electric field. We believe that the spats can assist walking by restraining and releasing body motion with different stiffness while walking, and conducted experiments to evaluate their effectiveness. It was found that the integrated electromyogram (IEMG) and maximal voluntary contraction (%MVC) of the rectus femoris muscle decreased during walking when wearing them which indicated that the gel spats designed in this study were effective in assisting walking.

## I. INTRODUCTION

Aging society as a global social issue has received much attention in the last few years. Considerable research has been done on walking assistance for supporting the elderly and the mobility impaired [1] [2] [3]. However, most of the traditional walking assist suits developed so far use an electric motor or air pressure actuator with a link to realize the assistance. It has many disadvantages, e.g. the suit is too big and heavy for the elderly with weak muscles. In addition, it is not easy to fit an individual with an exoskeletal device.

Akio Shizukai et al. proposed a new walking assist approach using functional clothes with highly elastic fabric. The proposed functional spats can only support motion of the hip joint flexion, and are not able to support the motion of the hip joint extension. Conversely, to obtain high elasticity in functional clothes, it is necessary to overstretch the fabric from its original shape which would be a burden for the elderly with weak muscles [4].

In our previous research, we developed a contraction type of polyvinyl chloride (PVC) gel actuator in which the PVC gel was sandwiched between an anode using a stainless steel mesh and a cathode [5]. The characteristics of the PVC gel actuator were also investigated [6]. The PVC gel actuator could move

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in the air, with a contraction of about 14 %, a response rate of 7 Hz, and an output force of 400 Pa/layer. We also found that the stiffness of the actuator increased as the applied dc field increased, similar to a human muscle. The characteristics of the PVC gel actuator are shown to be very effective for constructing an artificial muscle. In this study, we incorporated the PVC gel actuator within general spats to make new variable stiffness spats for walking assistance. The stiffness of the spats varies with on and off switching of an electric field. We believe that the spats can assist walking by restraining and releasing body motion with different levels of stiffness.

This paper is organized as follows: The PVC gel actuator is introduced in Section II. The variable stiffness gel spats are proposed in Section III, and their design is addressed in Section IV. The walking assistance experiment is discussed in Section V. Experimental results and discussion are presented in Section VI. Finally, some conclusions are addressed in Section VII.

## II. PVC GEL ACTUATOR

### A. Structure of the PVC gel actuator

PVC gel is made from PVC powder, dibutyl adipate (DBA) and tetrahydrofuran (THF) solvent with different weight ratios. The weight ratios of PVC and DBA in this study were adjusted to 10:40, 10:60 and 10:80, and the gels were denoted as DBA40 (10:40), DBA60 (10:60) and DBA80 (10:80), respectively. When both sides of the PVC gel are sandwiched by electrodes, electric charges (electrons) are injected from the cathode of the electrode into the gel, and migrate toward the anode. The accumulation of the electric charges promotes the electrostatic adhesive characteristics of the gel onto the anode, and creeping deformation appears on the anode surface. When the electric field is discharged, the PVC gel returns to its original shape very quickly.

Based on the properties of the PVC gel, we proposed the structure of an expansion and contraction type PVC gel actuator using a mesh type electrode [5]. The PVC gel is sandwiched between a stainless mesh as an anode and a cathode. Fig. 1 shows the deformation mechanism of the PVC gel when the DC field is applied. The PVC gel creeps up the anode and moves into the mesh hole, and the actuator shrinks. When the DC field is removed, it returns to its former shape because of its elasticity. Thus it performs the expansion and contraction deformation of the PVC gel actuator similar to a human muscle. By stacking up the layers it is operated as an expansion and contraction type actuator (Fig. 2).

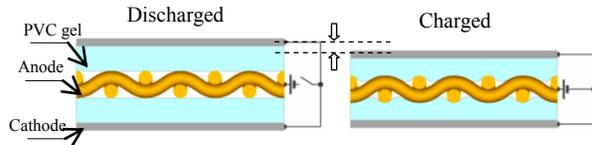


Figure 1. Contraction mechanism of a PVC gel actuator.

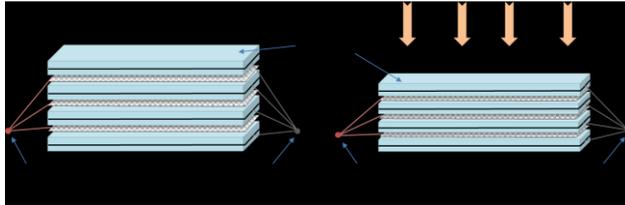


Figure 2. Illustrative diagram of a multi-layered PVC gel actuator.

In this study, we did not use the PVC gel actuator itself as an actuator for the assistance, but used its variable stiffness. It would need a high contraction rate to assist body motion if we used the mechanism of a PVC gel actuator as an actuator. From a previous study we found that it was difficult to obtain an adequate contraction rate. However, when using the stiffness variation to assist the motion, the displacement of PVC gel actuator is determined by the stiffness and it is possible to achieve a large displacement. So in this study, we focused on using the stiffness variation to support the motion of the body.

### B. Stiffness variation of PVC gel actuator

The PVC gel is sandwiched between the mesh anode and the foil cathode. When a DC field is applied, the PVC gel creeps on the anode and moves into the mesh holes. With the increase in the contact area between the gel and anode, the adsorption force between them increases, resulting in increasing stiffness of the PVC gel actuator.

We measured the stiffness of the PVC gel actuator as shown in Fig. 3. The top of the PVC gel was connected to a load cell and the bottom was fixed to the z-stage. We deformed it by actively modifying the micrometer of the z-stage and measured the stress  $\sigma$  using a load cell. The stiffness of the PVC gel is defined as  $G$  and the strain of the PVC gel actuator is  $\epsilon$ . The stiffness of the PVC gel actuator is defined by the following equation:

$$G = \frac{\sigma}{\epsilon} . \quad (1)$$

We measured the relationship between the stress and strain of three 5-layer PVC gel actuators with an applied DC field of 1200 V/mm. The PVC weight ratio was DBA40. The PVC gel was 0.5 mm thick, and 10 mm  $\times$  50 mm in size. The stainless mesh size of the anode was 20 wires to the inch. When the DC field was applied, the PVC gel actuator contracted and we set the load of the load cell to zero. We then adjusted the micro meter of the z-stage to actively deform the actuator. Fig. 4 shows the results of the relationship between the stress and

strain of the PVC gel actuator. From the results we can see that the stress is almost linearly proportional to the strain.

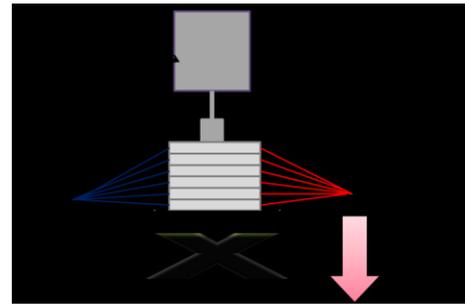


Figure 3. Measurement of the stiffness of PVC gel

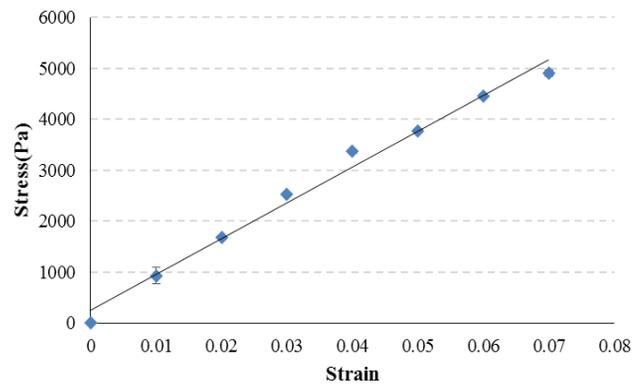


Figure 4. Relationship between stress and strain of the PVC gel actuator.

The stiffness is governed by several parameters, including the weight ratio of the PVC and plasticizer, the thickness of the PVC gel, the size of the mesh anode and the layers of the actuator. We conducted experiments to investigate the relationship between the stiffness and these parameters. We investigated the stiffness versus the weight ratios of the PVC and DBA of 10:40, 10:60 and 10:80, thicknesses of PVC gel of 0.5 mm, 1.0 mm and 1.5 mm, and mesh sizes of 20, 40 and 60. Fig. 5 shows the results of the PVC gel actuator stiffness versus different weight ratios of DBA to PVC, Fig. 6 versus different gel thicknesses, Fig. 7 versus different mesh sizes and Fig. 8 versus different numbers of layers of PVC gel. We found the PVC gel actuator with a weight ratio of DBA40, a gel thickness of 0.5 mm, an anode stainless mesh size of 20 and 15 layers of PVC gel had the greatest stiffness. To obtain the greatest stiffness the PVC gel actuator needed a lower weight ratio, thinner PVC gel and more layers of PVC gel actuator. In this study, we used the PVC gel actuator with a weight ratio of DBA40, PVC gel thickness of 0.5 mm and stainless mesh size of 20 in the design of the variable stiffness gel spats for walking assistance.

### III. VARIABLE STIFFNESS GEL SPATS

#### A. Proposal of variable stiffness gel spats

Fig. 9 shows the structure of the proposed variable stiffness gel spats used in this study. As shown in the figure, the PVC gel actuators are ranged along the thigh part of the spats, the two sides of the PVC gel actuator parts are fastened at the waist and knee. The material is a commonly used high elastic fabric (with 75 % polyester and 25 % polyurethane).



Figure 9. Structure of the variable stiffness gel spats.

#### B. Walking assistance with gel spats

The method of walking assistance with the variable stiffness gel spats is shown in Fig. 10. When the DC field is applied, the stiffness of the PVC gel parts change providing force to the thigh to assist the motion of the hip joint while walking. That is, when the user begins to raise a foot to take a step, the DC field is applied to the PVC gel part to increase the stiffness of the thigh part of the spats adding additional force to the thigh to assist raising the foot. When the foot steps to the ground, the electric field is turned off to decrease the stiffness of the PVC gel part making it easy to walk. In this manner, we believe variable stiffness gel spats are able to assist walking.

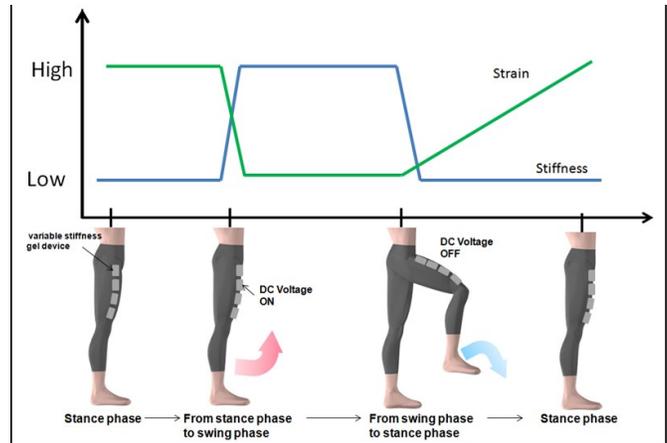


Figure 10. Walking assistance method using variable stiffness gel spats.

### IV. DESIGN OF VARIABLE STIFFNESS GEL SPATS

#### A. Structure of gel spats

Fig. 11 shows the structure of the designed variable stiffness gel spats used in this study. The type of the spats used is a short version without covering the knee, because for this study we needed spats with the properties of extension in the stance phase and contraction in the swing phase. Spats which

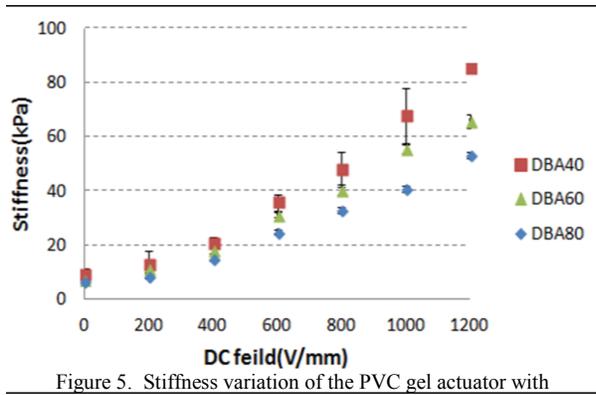


Figure 5. Stiffness variation of the PVC gel actuator with different weight ratios.

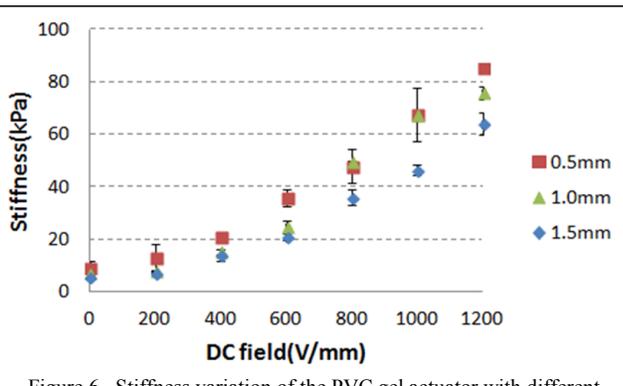


Figure 6. Stiffness variation of the PVC gel actuator with different thicknesses.

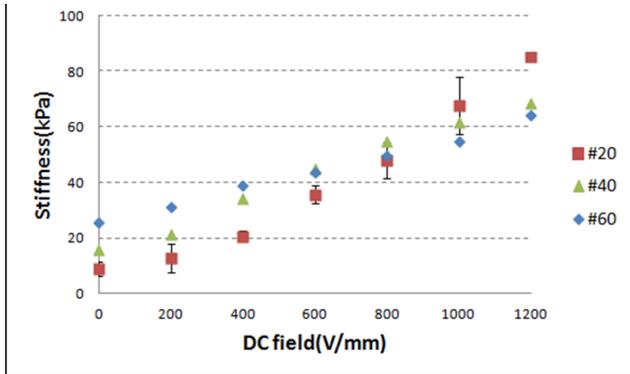


Figure 7. Stiffness variation of the PVC gel actuator with different mesh sizes.

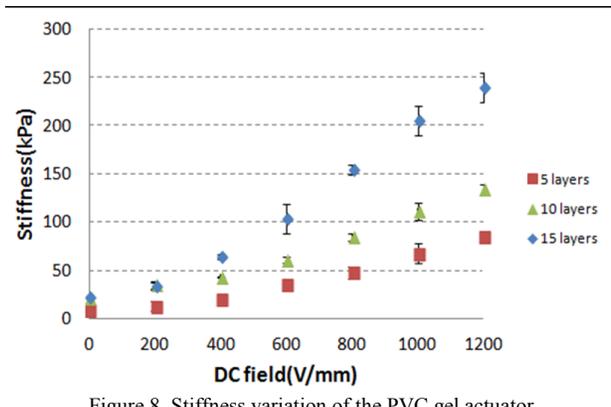


Figure 8. Stiffness variation of the PVC gel actuator with different numbers of layers.

are long enough to cover the knee will extend even in the swing phase which is not suitable for this study. As shown in Fig. 12, the variable stiffness PVC gel part is arranged decussately on part of the thigh. The joint of the PVC gel parts is just over the rectus femoris muscle. By such an arrangement, as shown in Fig. 5, when the foot raises to make a step, activating the electric field, the PVC gel part generates a force with a variation in the stiffness to assist walking. During the swing phase, the PVC gel part contracts and strain deformation occurs in the PVC gel part which will generate a force to assist the motion of the thigh. Each PVC gel actuator is connected by high stiffness stainless wires to create the generation force in the PVC gel part with no-losses during this assistance. Both sides of the PVC gel part are fixed by Velcro, which enables adjustment of the length of the PVC gel part to an individual and avoids breaking during removal.



Figure 11. Structure of the designed variable stiffness gel spats.

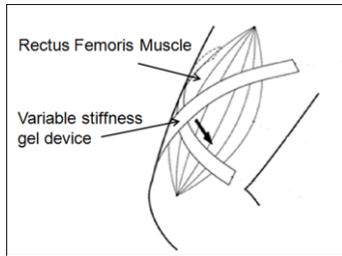


Figure 12. Arrangement of the variable stiffness gel spats.

### B. Deformation of the spats during walking

To design the PVC gel part for the variable stiffness gel spats, it is necessary to investigate the deformation of normal spats during walking. As shown in Fig. 13, the markers for motion capture are arranged equally at the top, middle and lower part of the thigh. The three dimensional position is captured by a motion capture device. We calculated the distance between each mark during walking from the stance phase to the swing phase and from the swing phase to the stance phase. We found that the spats shrink from the stance phase to the swing phase and extend from the swing phase to the stance phase in reverse order with a maximum deformation of 5.12 mm in the direction of the thigh.



Figure 13. Arrangement of markers to capture motion.

### C. Fabrication of variable stiffness gel spats

To avoid a break in the PVC gel part during walking, we measured the maximum strain on the PVC gel actuator. We found that the PVC gel actuator separated and broke when the strain reached 0.08. So the maximum strain on the PVC gel actuator was kept below 0.07. Considering the deformation of the spats, we calculated the layers of the PVC gel actuator using the following equations:

$$\delta = T\varepsilon, \quad (2)$$

$$T = \alpha x, \quad (3)$$

where  $\delta=5.12$  mm, is the deformation of the spats,  $T$  is the total height of the PVC gel actuator,  $\alpha$  is the height of each unit of the PVC gel actuator which is 1.2 mm and  $x$  is the number of layers in the PVC gel actuator. According to (2) and (3),  $x$  is about 60. In this study, we divided the 60 layer gel actuator into 4 parts, with 15 layers in each part. As shown in Section 2, the minimum stiffness of the PVC gel actuator was 20 kPa without the electric field, and the maximum stiffness was 220 kPa when the DC field was 1200 V/mm. The fabricated variable stiffness gel spats in this study are shown in Fig. 14.



Figure 14. The variable stiffness gel spats.

### D. Generation force of gel spats

We calculated the generating force of the gel spats with an 8 PVC gel actuator. We define the variation in stiffness as  $G$ , the strain in the spats during walking as  $\varepsilon$ , the cross-sectional area for each PVC gel actuator as  $A$  and the generating force from the variable stiffness as  $F$ . The angle between the PVC gel part and the thigh is  $\theta_1$ . According to Hooke's law, the generating force can be obtained by (4). As shown in Fig. 8 in Section II, the variation of stiffness  $G=80$  kPa when the DC field is 600 V/mm with 15 layers, the maximum strain  $\varepsilon=0.07$ ,

the cross-sectional area  $A=5.0 \times 10^{-4} \text{ m}^2$  and the angle  $\theta_1=20^\circ$ . Therefore the  $F$  for each PVC gel actuator is 2.63 N, and the total generating force is 21.05 N.

$$F = G \times \varepsilon \times A \times \cos\theta_1. \quad (4)$$

### E. Estimating the assistance effect

We made a model to estimate the assistance effect of the variable stiffness spats (see Fig. 15). As shown in the model, we added an additional weight of  $m$  kg at the knee and defined the angle of the hip joint from the vertical direction as  $\theta_2$  and the acceleration of gravity as  $g$ . So the relationship between the generating force and the additional weight can be expressed by (5):

$$F \cos\theta_2 = mg. \quad (5)$$

As we determined in Section D that the total generation force of the PVC gel part is 21.05 N, the angle  $\theta_2=20^\circ$  and  $g=9.8 \text{ m/s}^2$ . Using (4) we calculate the value of the  $m$  as 2.0 kg. This means it can support a weight of 2.0 kg by varying the stiffness of the PVC gel part. To investigate the assistance effect, we conducted an electromyogram (EMG) test on the rectus femoris muscle with and without the additional weight of 2.0 kg. Fig. 16 shows the result of the EMG test. From the result we see that the %MVC in the case of non-load on the knee is 18% smaller than in the case of a 2.0 kg load on the knee. This suggests that it has the same assistance effect when wearing the variable stiffness gel spats while walking.

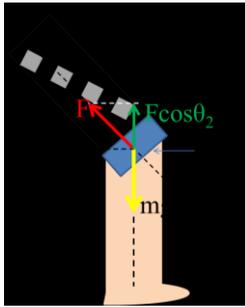


Figure 15. Model for estimating the assistance effect of variable stiffness gel spats.

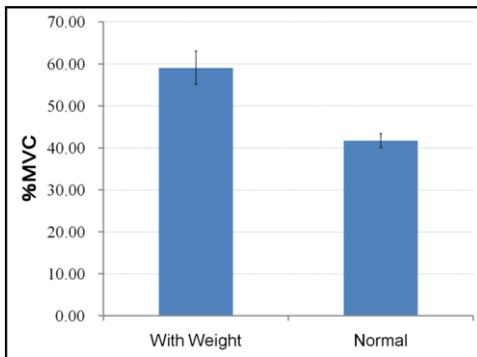


Figure 16. %MVC of the estimated assistance effect for variable stiffness gel spats.

## V. EXPERIMENTS

In this study, we conducted two experiments to evaluate the

effectiveness of the variable stiffness of gel spats. In the first experiment, we endeavored to find the assistance effect for the motion of lifting a foot. Five, healthy university student males, with an average age of 20 years, were asked to participate in the experiment. The method for the experiment is shown in Fig. 17. The subjects wore the gel spats with the PVC gel part arranged only on the right part of the spats. The subjects lifted their right foot from the standing position at the sound of a buzzer. On hearing another buzzer, the subjects returned the right foot to the standing position. The DC field (300 V) for the PVC gel part was turned on and off by hand at the moment the subject raised or lowered their foot. Two computers were used to apply power to the gel spats and to measure the electromyogram (EMG). We measured the EMG of the subjects' rectus femoris muscles when wearing normal spats and when wearing gel spats.

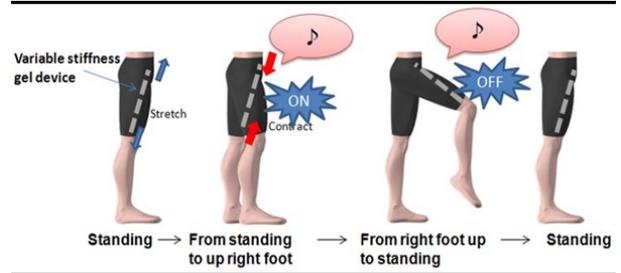


Figure 17. Method of the experiment for assistance effect.

In the second experiment, we investigated the assistance effect while walking. We asked the 5 healthy male university students to participate in the experiment. The subjects were asked to walk at a pace governed by the sound of a metronome. The DC field (300 V) was turned on and off at the moment of lifting and laying down the right foot to change the stiffness of the gel spats to assist walking. The electromyogram (EMG) of the subjects' rectus femoris muscles and biceps femoris muscles were measured when wearing normal spats and when wearing gel spats.

## VI. RESULTS AND DISCUSSIONS

Figs. 18 and 19 show the results of the first experiment. Fig. 18 shows the integrated electromyogram of the rectus femoris muscle. The x axis is the normalization of the motion time. We define the stance phase of the right foot as 0, the swing phase as 1 and when the right foot returns to the stance phase as 2. From the figure we observe that when lifting the foot, the rectus femoris muscle is used to support the motion. In the period from 0 to 1, the DC field is turned on and we can see that with the assistance of the gel spats, the IEMG is lower than when wearing normal spats. In the period from 1 to 2, the DC field is turned off and the value of IEMG is almost the same as when wearing normal spats. In addition the average %MVC when wearing gel spats is 6 % lower than in the case of normal spats with a significant difference of 5 % (see Fig. 19). This suggests that wearing the variable stiffness gel spats reduces the load on the rectus femoris muscle when

lifting a foot.

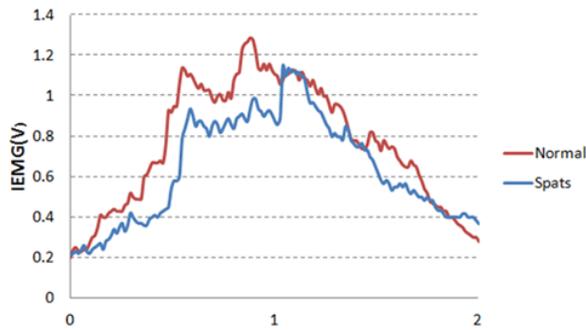


Figure 18. IEMG of the Rectus Femoris Muscle in the first experiment.

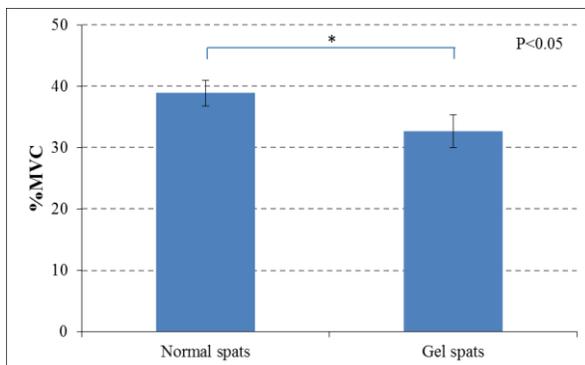


Figure 19. %MVC of the rectus femoris muscle in the first experiment.

We obtained similar results in the second experiment as shown in Figs. 20 and 21. In the period from 0 to 1, with the assistance of the gel spats, the IEMG of the rectus femoris muscle was lower than for normal spats. In the period from 1 to 2, the DC field was turned off and the value of IEMG was almost the same as for normal spats. In addition the average %MVC when wearing gel spats was 6 % lower than wearing normal spats with a significant difference of 5 %. However we did not obtain a significant difference in the IEMG of the biceps femoris muscle in the two cases for this experiment. This indicates that wearing the variable stiffness gel spats reduces the load on the rectus femoris muscle during walking.

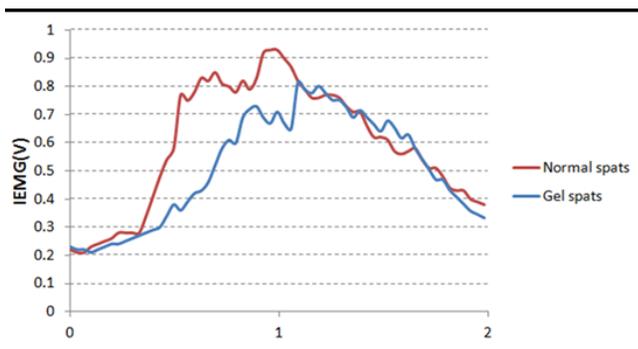


Figure 20. IEMG of the rectus femoris muscle in the second experiment.

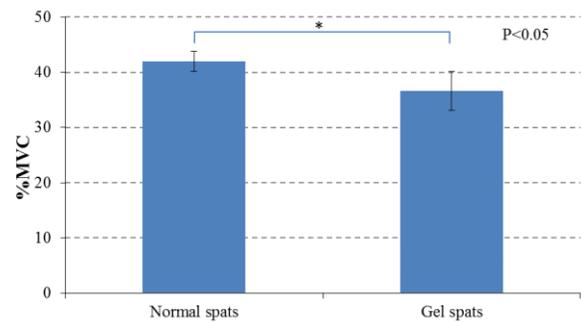


Figure 21. %MVC of the Rectus Femoris Muscle in the second experiment.

## VII. CONCLUSIONS

In this study, we have proposed a design for variable stiffness gel spats using the PVC gel for walking assistance. We have developed a contraction type PVC gel actuator, and found the minimum stiffness of the PVC gel actuator with the weight ratio of DBA40, PVC gel thickness of 0.5 mm, anode mesh size of 20 and with 15 layers is 20 kPa without an electric field, and a maximum stiffness of 220 kPa when the DC field is 1200 V/mm. We incorporated the PVC gel actuator in generally used spats to create new variable stiffness gel spats and conducted two experiments to evaluate their effectiveness. The experimental results in the two experiments show that both the IEMG and the %MVC of the rectus femoris muscle decreased with the assistance of the gel spats which suggests that wearing them is effective for walking assistance.

In future work, we will research improving the properties of the PVC gel part to develop more powerful spats with the PVC gel for walking assistance. To accurately investigate the effectiveness when wearing the gel spats, we will create models to measure the practical characteristics (e.g. generating force) and evaluate other aspects of their effectiveness.

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