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Test Method for Contact Safety Assessment of a Wearable Robot -Analysis of Load Caused by a Misalignment of the Knee Joint-

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***Abstract*— Wearable robots have finally reached a point at which they can be put to more practical use. However, methods for assessing their safety have yet to be properly established. Furthermore, for ethical reasons, such assessments must be conducted without exposing the human user to unnecessary danger. Therefore, in this study, a lower–leg dummy for the safety assessment of a wearable robot was developed to evaluate the effects of a misaligned knee joint.**

I. INTRODUCTION

A. Background

The importance of development of living assist robots has increased, as improvements in the quality of life and productivity of aging societies are becoming more vital. Wearable power–assist robots (hereafter, ”wearable robots”) are a kind of living assist robots that are fixed to the human user through a device such as a cuff, and provide power assistance to the wearer.

However, compared to other types of human–assisting machines, the degree of safety of wearable robots should be of greater consideration, as they make direct contact with the user. Therefore, before wearable robots can be used by the general public, a proper safety assessment is needed. ISO 13482 will become an industrial standard for service robots. However, a proper concrete testing method and a quantitative target have yet to be adequately determined. For ethical reasons, a real human user should not be used as a test bed. Therefore, the development of a test method that does not use a real human user is required.

Some robot designs do consider contact safety. A redundant degree of freedom, back–drivability, and the use of proven safety braces are a few of the safety measures used in such cases [1], [2]. However, studies in these areas have mainly focused on the development of a particular mechanism or the robot itself. Therefore, safety analyses such as risk assessments and a verification of safety functions remain inadequate from the viewpoint of safety engineering.

Furthermore, while a study has been conducted on the relationship between the force applied to the skin and the resulting feeling of discomfort [3], with an emphasis placed on a safety evaluation, a prediction of the force applied by a wearable robot remains a necessity for a proper safety assessment.

In addition, a study on a mechanism mimicking the complex motion of a human joint was also conducted [4]. Using the proposed mechanism, the study aimed to evaluate the safety of a wearable robot. However, the researchers have yet to measure the force applied to an actual human user.

Currently, development groups and robotics companies are in charge of safety on the user side, and a test method for an assessment of contact safety has yet to be established. Therefore, in this study, a risk assessment of a wearable robot was conducted. A lower–leg dummy was also developed for the safety tests [5], [6].

B. Misalignment between the knee joints of a human user and a wearable robot

First, hazard identification for contact safety was conducted through a risk assessment. In this study, rehabilitation is assumed to be the main purpose of the wearable robot. Therefore, a fall is excluded from this study, as a user undergoing rehabilitation should be properly supported by a bar or physical therapist. Examples of the identified hazards are listed in table I. The table suggests that the user of a wearable robot is at a risk of injury to the skin, muscle, and bones.

The present study focuses on a misalignment of the center of rotation of the knee joints between a user and a wearable robot. Although other kinds of hazards, including those related to mechanical and electrical issues, are also important to the safety of a wearable robot, they can be considered based on previous safety assessment methods. In addition, international standards for these types of hazards have been previously established [7].

Fig. 1 shows the difference between the rotation mechanism in the knee joint of a human and a wearable robot. A human knee joint consists of a femur and a tibia. The condyle of the femur is shaped like an ellipse, while the upper side of the tibia is shaped like a plane. Therefore, the femur slides on the tibia when the knee is bent. As a result of this composite motion, the center of rotation moves with the bending angle [5], [8], [9], [10], [11], [12]. In contrast, the knee joint of a general wearable robot consists of a pin joint. Therefore, the centers of rotation of the knee joints of both the human and the wearable robot become misaligned with the bending of the knee, even when their initial positions are carefully aligned.

Currently, many wearable robots aimed at practical use have a pin joint at the knee. Therefore, an evaluation of

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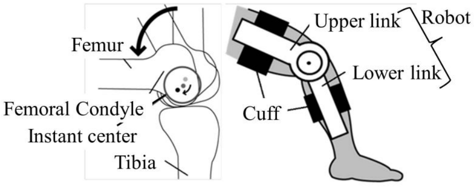
TABLE I

ERGONOMIC HAZARD OF WEARABLE ROBOT

	Hazard source	Potential consequence result
Ergonomic hazards	Misalignment at center of rotation of joint	Overload at human joint
	Decrease in DOF of joint	Overload at human joint
	Sudden robot motion	Muscle damage
	Constriction of fitting parts	Internal bleeding, Abrasion of skin



(a) Human knee (b) Robot knee

Fig. 1. Difference of knee rotation mechanism

the risk posed by a misalignment of the center of the knee is quite important. In addition, a misalignment will almost certainly occur when the user wears a wearable robot, as the center of rotation of the knee is difficult to be seen externally. These kinds of misalignments also create a problem for the user. A misalignment of the knee joint will displace the position between the user and the wearable robot, causing an increase in the force applied to the user by the wearable robot (cuff force).

A second kind of motion, rotation, also occurs in the lower leg of a human user. A rotation motion occurs when the lower leg is almost fully extended, and the amount of such rotation can be up to several degrees. However, many wearable robots do not consider this factor. Therefore, a rotation motion may also cause a displacement of the cuff position and the cuff force.

The most important difference between the change of the center of rotation and the rotation motion is the effect of the misalignment. A misalignment at the sagittal plane probably causes a change in the relative position between the user and the wearable robot. This means that the displacement and force are not necessarily proportional to the misalignment. Therefore, in this study, the effect of lower–leg movement along the sagittal plane is analyzed prior to the rotational motion.

C. Suggested contact safety test of a wearable robot

The final aim of this study is the suggestion of a contact safety test of a wearable robot. In our test, a wearable robot is operated using a lower–leg dummy, and the forces applied to the skin and bones of the dummy are measured and evaluated. The measurement should be conducted under two types of conditions. The first type is the actual condition, such as walking, standing up, or sitting down, while the second type is the elemental condition, such as the flexion or extension of the joints. The force applied to on the dummy should be sufficiently small under such conditions.

The maximum burden should be determined from a medical and biomechanical viewpoint. Even though the applied force is not harmful to a younger and healthier user, the elderly or people with certain diseases may run the risk of injury. Therefore, the upper limit of applied force must be carefully determined. On the other hand, the dummy should be able to mimic the human motion of the joints and skin. In this paper, only the knee joint is discussed. However, the dummies of other joints are considered now.

II. MEASUREMENT OF LOWER LEG MOTION WITH BENDING OF THE KNEE

Many studies have suggested that the center of rotation in the human knee joint moves with a bending of the knee [5], [8], [9], [10], [11], [12]. However, these studies have focused only on the knee joint itself. In contrast, when operating a wearable robot, the user receives force from the robot through the cuff. Therefore, the motion of the user's lower leg at the cuff location needs to be analyzed to estimate this force. One effective way to measure the displacement at the cuff is to conduct a physical experiment.

Fig. 2 shows an overview of such an experiment, which aims to measure the displacement between a user and a wearable robot at the cuff location. In this experiment, the user's thigh was fixed to a pole, which was fixed to the ground with the thigh of the wearable robot at a natural standing position. Only the lower thigh of the user was continuously bent.

In this sequence, the length between the center of rotation of the wearable robot and the user' s cuff location at the sagittal plane was measured. Motion capture equipment (Motion Analysis, MAC 3D) was used to measure the position and length during the experiment. The angle of the user ' s knee is defined as the angle between the vertical line and the line connecting the marker at the center of the knee to the marker at the user ' s cuff location. The average measurement error caused by the motion capture system itself is 0.07 mm.

Fig. 3 shows the results of ten flexion extensions. This figure suggests that the length between the center of rotation of the knee joint and the cuff location of the user's lower thigh increases with the bending angle. The tissue between the surface of the skin and the bone generally moves with a bending of the knee. Therefore, the results in Fig. 3 include the effect of the movement of the human skin and tissue, in addition to the effect of the movement of the center of rotation. However, an actual wearable robot is not attached to the human bone directly. Therefore, these experimental

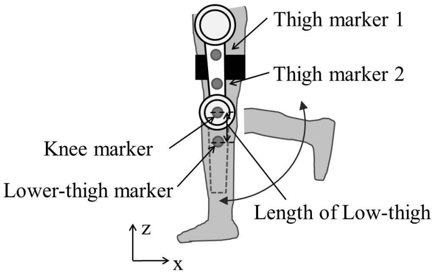


Fig. 2. Flexion-extension of a human knee with the upper link of a robot fixed by a cuff

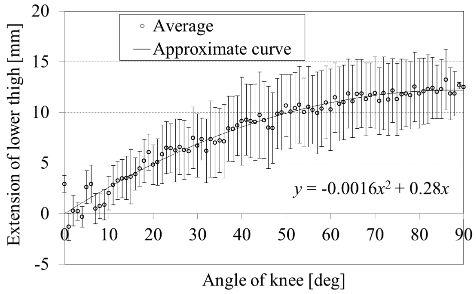


Fig. 3. Extension of distance between the human knee joint and the low cuff

conditions are considered to be sufficiently similar to the actual conditions.

III. ANALYSIS OF EFFECT OF AN INITIAL MISALIGNMENT

It is important to attach a wearable robot correctly, since an incorrect attachment will endanger the wearer. However, it is difficult to eliminate the misalignment at the knee joint completely, as it is quite difficult to identify the center of rotation of the joint externally. Therefore, a certain degree of misalignment should be considered when attaching a wearable robot. To predict the load placed on the user, an estimation of the displacement at the cuff location caused by a misalignment of the knee joint is useful. To estimate such a displacement, the relationship between the misalignment of the center of rotation and the displacement of the cuff should be modeled.

In this study, a wearable robot fixed to the user through the cuff at the thigh and lower thigh is considered (Fig. 1). In addition, the lower leg of the user is considered as fixed parallel to the wearable robot except when the axis of the revolution of the knee is misaligned. Three directions of misalignment, up–down, forward–backward, and inner–outer rotations, are considered in this model. At the cuff location of the lower thigh , the displacement in the longitudinal direction is of particular focus.

First, the rotation of the axis of the knee revolution is modeled. Fig. 4 shows the geometry of the lower legs of the wearable robot and the user. β denotes the rotation angle between the axis of revolution of the knee and the wearable robot. A misalignment of the axis of rotation at the sagittal plane causes a displacement of the cuff position in the longitudinal direction of the lower thigh with a bending of the knee.

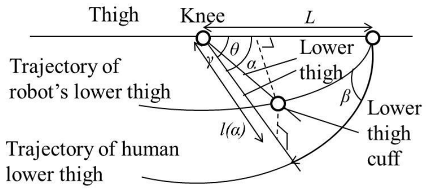


Fig. 4. Geometry of lower leg model to simulate the misalignment of rotation axis

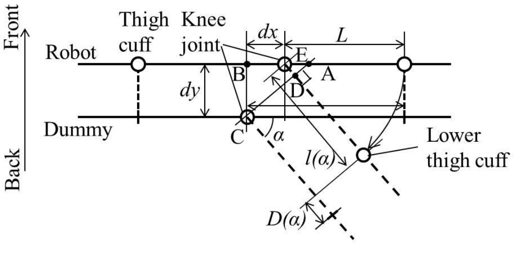


Fig. 5. Geometry of lower leg model in sagittal plane

Equations (1)–(5) calculate the displacement between the cuff positions of the wearable robot and the user at the sagittal plane of the wearable robot. A bending of the knee shortens the length between the center of the knee joint and the cuff location. Therefore, a misalignment of the rotation axis drags the lower thigh of the user toward the direction of the knee region. As a result, the displacement of the cuff position increases with a misalignment of the rotation axis.

$$L\cos\gamma\cos\alpha = L\cos\theta \tag{1}$$

$$L\cos\gamma\sin\alpha = L\sin\theta\cos\beta \tag{2}$$

$$\begin{aligned} l(\alpha) &= L\cos\gamma \\ &= \frac{\cos\beta}{\sqrt{\cos\beta^2\cos\alpha^2+\sin\alpha^2}} \end{aligned} \tag{3}$$

Next, misalignments of the up–down and forward–backward directions along the sagittal plane are considered. Fig. 5 shows the geometry of the wearable robot and the lower leg of the user at the sagittal plane. As the initial misalignment, two parameters, dx and dy, are used, since the effect of a misalignment differs according to the direction. A displacement of the cuff position is calculated using (5). As a result of this calculation, a misalignment in the backward or upward direction increases the displacement toward the centrifugal (plus) direction, while a forward or downward misalignment has the opposite effect.

$$\begin{aligned} \mathrm{DE} &= \mathrm{AE}\cos\alpha \\ &= (dy\tan\alpha - dx)\cos\alpha \\ &= dy\sin\alpha - dx\cos\alpha \end{aligned} \tag{4}$$

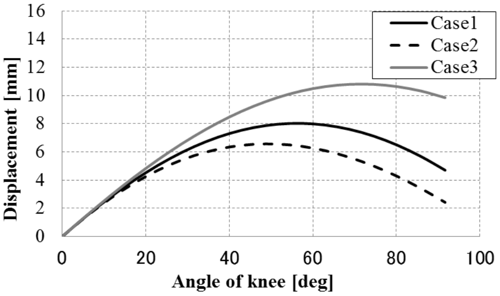


Fig. 6. Displacement at the cuff position related to the combination of misalignments

$$\begin{aligned} D(\alpha) &= l(\alpha) - (l(0) - dx) + \mathrm{DE} \\ &= L(\frac{\cos\beta}{\sqrt{\cos\beta^2 \cos\alpha^2 + \sin\alpha^2}} - 1) \\ &\quad + dy \sin\alpha + dx(1 - \cos\alpha) \end{aligned} \tag{5}$$

Finally, a combination of misalignments in different directions is considered. Equation (3) also indicates how misalignments of the up–down, forward–backward, and inner–outer rotations independently affect the displacement of the cuff position at the sagittal plane . Therefore, in the case of a combinatorial misalignment, the total displacement at the cuff location can be calculated as the linear sum of the displacement of each misalignment. The displacements of various parameters are shown in Fig. 6. Case 1 indicates a condition in which $dx = -10\,\mathrm{mm}, dy = 15\,\mathrm{mm}$, and $\beta = 0\,\mathrm{deg}$; case 2 corresponds to $dx = -10\,\mathrm{mm}, dy = 15\,\mathrm{mm}$, and $\beta = 10\,\mathrm{deg}$; and finally, case 3 is for $dx = -5\,\mathrm{mm}, dy = 15\,\mathrm{mm}$, and $\beta = 0\,\mathrm{deg}$. The figure shows that the tendency of a force applied to the cuff (cuff force), such as the maximum force and its angle, changes based on these parameters.

In this section, a displacement between a wearable robot and its user caused by an initial misalignment of their centers of rotation is analyzed using a simple model. The results of this simulation suggest that an independent displacement is caused by each misalignment. In addition, the trend of displacement caused by each misalignment is calculated.

IV. ANALYSIS OF FORCE OF A DUMMY USER ' S LOWER THIGH CUFF

An experiment using a dummy was conducted to evaluate the cuff force. An overview of the dummy used is shown in Fig. 7. This dummy consists of a thigh, lower thigh , and a knee joint. Although the knee of the dummy has a pin joint, the lower thigh has an extension mechanism. Therefore, the trajectory of the motion of the cuff position of the human user can be mimicked using this mechanism.

The extension rate is based on the experimental data shown in Fig. 3. In addition, to realize the different parameters, the relative position between the dummy and the wearable robot varied through the use of adjustable parts. Furthermore, an encoder was attached at the knee joint to measure its angle and to control the extension mechanism of the lower thigh. The surface of the dummy has a simple cylindrical shape, and its diameter was designed using the database in [13] to correspond to the average adult human. In addition, an artificial skin was applied to the surface of the dummy.

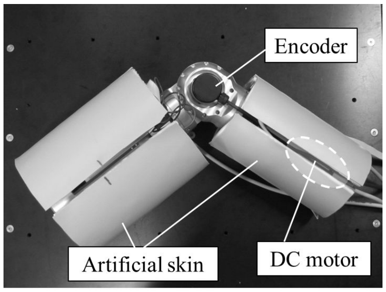


Fig. 7. Overview of the lower leg dummy

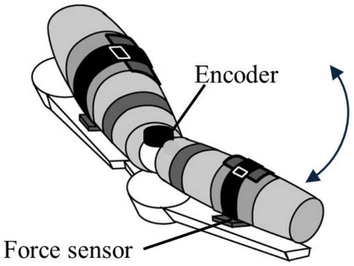


Fig. 8. Overview the the experiment condition

A wearable robot was then attached to the dummy, as shown in Fig. 8. A force sensor was attached to the lower–thigh cuff of the wearable robot, and the sensor measured the force applied to the dummy by the wearable robot to evaluate the burden placed on the skin. In further research, the force applied to the high cuff will be measured to evaluate the burden placed on the knee joint. The compliance of the fixed area in the longitudinal direction was $0.2\,\mathrm{mm/N}$. This compliance was measured using a tension and compression testing machine. This parameter does not completely match that of a human user owing to the underdevelopment of the artificial skin. However, the same tendency was measured experimentally using a human lower leg at the prospective degree of displacement and cuff force.

A. Effects of the initial misalignment at the center of the knee

In a bending experiment, a wearable robot was attached to the dummy. The parameters of the misalignment were initially set as follows: $\beta = 0$, $l = 150\,\mathrm{mm}$, $dx = 0$, and $dy = 15\,\mathrm{mm}$. The parameters of the initial misalignment were then changed to evaluate their effects. In these experiments, the extension mechanism of the lower thigh was stopped to exclude the effect of the movement of the center of rotation.

Fig. 9– 12 compare the results of the force measurements and calculations of the displacement at the lower thigh cuff. These figures show that the force of the lower thigh cuff and the displacement of the cuff position have similar tendencies, which suggests that a displacement caused by an initial

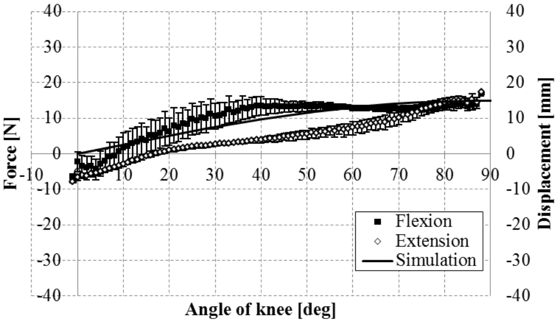


Fig. 9. The lower thigh cuff force ($dy = 15\,\mathrm{mm}$)

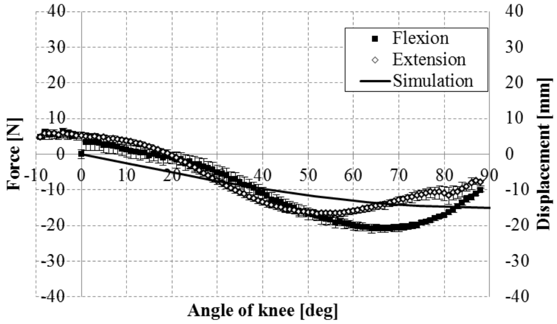


Fig. 10. The lower thigh cuff force ($dy = -15\,\mathrm{mm}$)

misalignment of the knee applies force to the human user. However, the effect of a twisting motion, as shown in Fig. 12, causes a particular problem. In this case, the increase in the force is relatively larger than that in the displacement, as compared to the case shown in Fig. 9, in which a stirring motion is observed at the cuff; this effect is shown in Fig. 12 as a shift in the force at $0, \mathrm{deg}$. These results suggest the existence of a more complex mechanism in the case of a twisting motion.

The cuff force can be simulated through a simple multiplication of the compliance and displacement at the cuff position. However, the magnitude of the measured force does not correspond to the force calculated using the compliance or displacement. The calculated forces are several times higher than the measured values. One assumed reason for this is the twisting movement of the fixed area of the thigh. In the calculation, the human thigh is fixed parallel to the wearable robot. However, the fixed area of the thigh rotated during the experiment. Therefore, the effect of the lower–thigh displacement was possibly absorbed into the rotation motion of the thigh.

B. Effect of an ergonomic misalignment at the center of the knee joint

A misalignment of the center of the knee caused by a movement of the center of rotation is mimicked by the lower–leg dummy through the use of a lower–thigh extension mechanism. In this section, the effect of the misalignment of the center of rotation is evaluated using the dummy. To determine the effect of an ergonomic misalignment, the experimental conditions were set to correspond to the non–extension cases mentioned below. Fig. 13 shows the results of a bending experiment using a dummy attached to the lower–thigh extension. A comparison of Figs. 9 and 13 shows the effect of the lower–leg extension.

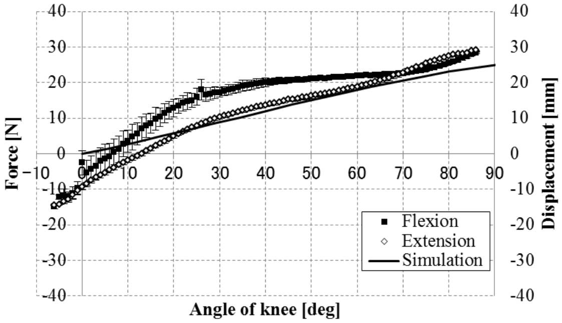


Fig. 11. The lower thigh cuff force ($dx = 10\,\mathrm{mm}, dy = 15\,\mathrm{mm}$)

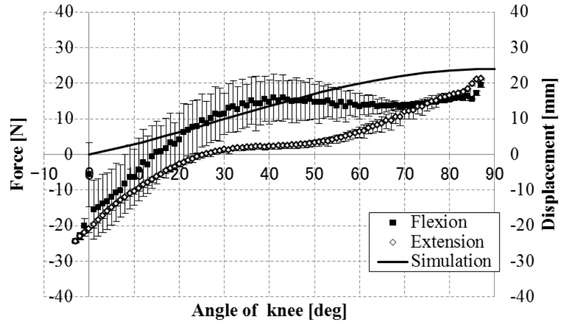


Fig. 12. The lower thigh cuff force ($dy = 15\,\mathrm{mm}$, and twist)

These figures indicate that a lower–thigh extension increases the force of the lower–thigh cuff by approximately $20mathchar` - 50\,\mathrm{deg}$. The lower–thigh extension pushes the dummy's lower thigh toward the foot, thereby applying force to the cuff. However, the force is reduced by the twisting movement of the thigh, which is the same as that in the non–extension cases.

Furthermore, the same tendency can be seen in the other cases shown in Figs. 14– 16. An increase in the force of around $20mathchar` - 50\,\mathrm{deg}$ commonly occurred. In

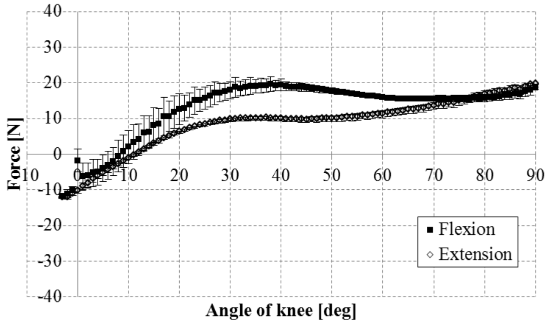


Fig. 13. The lower thigh cuff force with lower thigh extension ($dy = 15\,\mathrm{mm}$)

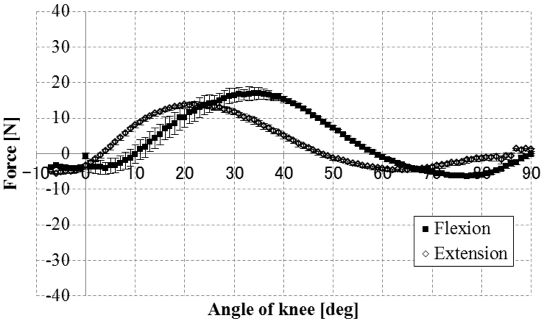


Fig. 14. The lower thigh cuff force with lower thigh extension ($dy = -15\,\mathrm{mm}$)

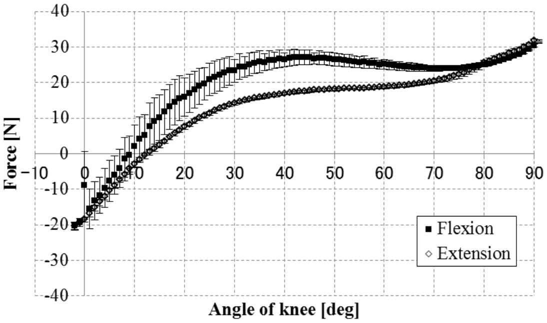


Fig. 15. The lower thigh cuff force with lower thigh extension ($dx = 10\,\mathrm{mm}, dy = 15\,\mathrm{mm}$)

addition, in some of the cases, the range of force increased relative to a non–extension case. This result suggests that the movement of the center of rotation causes an increase in the force of the lower–thigh cuff under certain conditions.

V. CONCLUSIONS

This study focused on the risks posed by the use of a wearable robot, such as the initial misalignment of the center of the knee and the movement of the center of rotation caused by the ergonomic mechanism. First, the displacement between the user and the wearable robot at the cuff position caused by the ergonomic mechanism was measured using a motion capture system. Second, the displacement at the cuff caused by the misalignment of the knee was analyzed using a mathematical model. Finally, a lower–leg dummy that can mimic the displacement at the cuff attached to the user's lower leg was introduced.

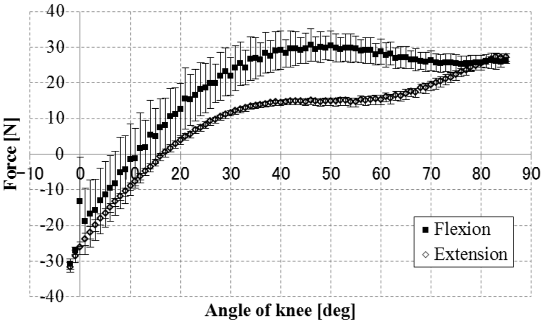


Fig. 16. The lower thigh cuff force with lower thigh extension ($dy = 15\,\mathrm{mm}$, and twist)

An experiment using the lower–leg dummy was conducted to evaluate the effect of a misalignment. As a result of the experiment, the force of the lower–thigh cuff showed the same tendency as in the simulation. Although the magnitude did not correspond to the simulation results, the results suggest that a twisting movement at the thigh cuff reduces the amount of force. Therefore, the motion and force at the thigh cuff should be considered. As a result, the effect of a misalignment of the initial setting was measured to a certain degree, which suggests the importance of the movement of the center of rotation when evaluating the force of the lower–thigh cuff.

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