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FULL PAPER

Simulated crepitus and its reality-based specification using wearable patient dummy

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Physical therapists are trained in manual examination techniques to test the impaired motor functions of patients. In this study, we have introduced a wearable robotic dummy joint to simulate disordered joint resistances or behaviors to support physical therapists in learning such techniques. We developed a discontinuous joint friction model based on a stick-slip phenomenon to simulate knee joint resistances caused by crepitus, a typical symptom accompanied by osteoarthritis. Practicing therapists participated in a reality-based evaluation test and specified acceptable parameter sets to adjust the simulated crepitus for the exoskeletal patient robot. The simulated crepitus and wearable dummy joint are expected to support the training of physical therapists.

Keywords: rehabilitation; patient dummy; wearable robot

1. Introduction

Physical therapy has been attracting increasing attention for the important role it plays in helping stroke or arthritis patients to recover their impaired motor functions. Rehabilitation improves patients' quality of life and reduces medical costs by enhancing their recovery.

Patient rehabilitation is supported by trained physical therapists. In their training, therapists learn manual examination techniques using which they manually move and palpate affected body parts to investigate biomechanical and neurological reactions. Then, they understand pathology and identify the site to be treated. During manual examinations, therapists flex and stretch the patient's joint to understand the degree of sensory-motor impairment based on resistance patterns, range of joint motion, and patient's complaints such as pain. The resistance patterns of disordered joints differ from patient to patient. Therefore, trainee therapists need to experience various patient cases to learn these testing techniques. However, they enjoy few opportunities to interact with real patients in training institutions. Even during internship training, it is ethically problematic for unlicensed trainees to treat patients. To supplement the dearth of experiences available in training institutions, studies have focused on patient robots to support physical therapists in learning manual techniques. Asahi Denshi Corp. et al. developed a robot that simulates the muscle rigidity and limited motion range of a disordered knee joint.[1] Kikuchi et al. demonstrated a knee joint robot using a magnetorheological fluid clutch and servomotor to generate large and dynamic resistances, respectively.[2,3] Other researchers

developed elbow robots to simulate spasticity.[4–6] These studies simplified a robot joint as a uniaxial one. Several researchers have also focused on complex human joint motions. Takahashi et al. simulated the stretch and shortening of the forearm due to the extension and flexion of the upper extremity using an oval cum.[7] Morita et al. developed a robotic knee with rotational movement accompanied by knee stretch and flex.[8] Oki Electric Industry Co. Ltd. introduced a rehabilitation training robot that has six degrees of freedom.[9] Overall, many research groups have developed patient dummy robots for supporting the training of physical therapists in manual examination techniques. To realize the widespread practical use of these robots, it is crucial to broaden the types of symptoms that are simulated.

This study aims to simulate crepitus, a discontinuous joint friction condition caused by osteoarthritis (OA), using an educational patient dummy robot. Earlier studies mainly simulated joint rigidity, contracture, and spasticity. However, OA has not yet been simulated, partly because studies on patient robots for physical therapy are still in their initial stage. Presently, OA is the most common causal symptom for those who require support providers in daily living in Japan.[10] Therefore, enabling patient robots to simulate crepitus will improve their effectiveness. It is preferable that the simulation is grounded on the data collected by actual knee OA patients. However, owing to their possible mental and physical burdens and little expected interest that the patients would receive through and after data collection procedures, we avoided the measurement of actual patients. Alternatively, as a criterion to maintain the validity

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of the simulated symptom, we employed the subjective similarity that the practicing clinicians perceive.

This study also introduces a wearable dummy robot to simulate joint impairment. To the best of the authors' knowledge, this is the first study to do so. Wearable dummies should allow trainee therapists to experience complex motions of human joints, skin, and bone features of humans, as well as simulated joint disorders. Owing to their high realism and simplicity, wearable dummies can be a new approach for patient dummies.

The authors have previously presented the concepts of the wearable dummy and the crepitus model.[11,12] This study has additionally specified a model that represents the typical crepitus experienced by physical therapists through reality-based rating tasks.

2. Wearable dummy knee joint

Some technical issues must be considered for the development of patient dummies. First, the simulation accuracy must be ensured. For example, during manual examination, some symptoms involve dynamic or large reaction forces, which the dummy needs to precisely simulate. Second, the human joint is intrinsically different from robotic or mechanical joints. For example, the human knee joint undergoes minor stretch or contraction and rotation when it extends and flexes; therefore, it has at least three degrees of freedom. Finally, the dummy should mimic humans in terms of factors, such as the appearance, skin, and bone features, so that the trainees feel that they are facing patients. Balancing these issues generally involves a trade-off between the cost and the simulation accuracy.

Figure 1 shows a wearable dummy joint used in this study and worn by a healthy relaxed person. The dummy joint has a simple construction, consisting of one motor and two links. Each link is fixed to the subject's lower and femoral thighs through a brace called a cuff. Trainees practice examination techniques in pairs, with one acting as the patient and the other acting as the therapist performing manual examinations. The trainee grasps the lower thigh of the mock patient wearing a dummy joint and flexes or extends the knee. The wearer is relaxed and does not exert any voluntary movements. The motor installed on the dummy joint simulates resistance forces around the knee, depending on the simulated symptoms.

The dummy joint has neither the rotational nor the sliding mechanisms of the human knee joint. These mechanical differences between the human and wearable dummy are resolved by the elasticity of human body tissues or clothes. Therefore, the trainee can experience the inherent minor rotations and slides of the human knee joint. Furthermore, unlike with previous dummy robots, the trainee touches a real human leg, skin, and bones, which makes the patient simulator highly realistic. It should be noted that this dummy delivers joint resistance forces through nonrigid

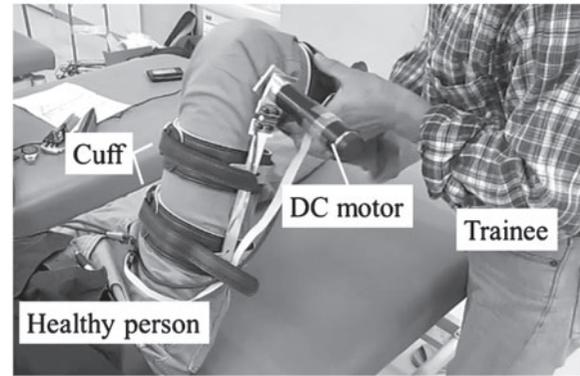


Figure 1. Wearable dummy joint to simulate knee-related disorders. Trainee extends and flexes the lower thigh to experience simulated joint resistances.

connections between the cuff and the human leg. Small forces tend to be decayed by the wearer's cloth and body tissues and are therefore not imparted to the trainee's hand. The influence of such attenuation remains to be clarified; nonetheless, this approach is apparently applicable to symptoms represented by sustained joint resistances, such as contracture and rigidity.

A geared DC motor (RE35, Maxon, stalling torque 949m N·m, 1/86 geared) was installed on the exoskeletal robot, which was fitted to a healthy femur and lower thighs using cuffs and cloth bands. The motor was controlled by a microcomputer through a motor driver (Maxon, 4-Q-DC servo amplifier ADS 50/5) with a PI current controller. The microcomputer also acquired the joint angle from an encoder mounted on the motor. We compensated for the kinetic friction force of the reduction gear, which was measured as ~ 0.2 N·m regardless of the rotary speed.

In this study, the patient robot is aimed for the training of examination techniques. It is also worthwhile to use it for the training of therapeutic techniques. During physical therapy, such as joint stretching, patients may feel pain and take resistive behaviors against the therapist's treatment owing to fear. To extend the use of patient robots to the training of therapeutic techniques, such patients' reactivity needs to be considered.

3. Resistance model of crepitus

3.1. OA and crepitus

In this study, we focus on crepitus, a discontinuous joint friction condition that is one of the major symptoms of OA patients. OA is a chronic painful arthropathy characterized by the disruption and potential loss of joint cartilage along with other joint changes.[13] Worldwide, 9.6% of men and 18.0% of women over 60 years of age are estimated to have symptomatic OA.[14] In Japan, an epidemiologic study estimated 25 million potential knee OA patients [15];

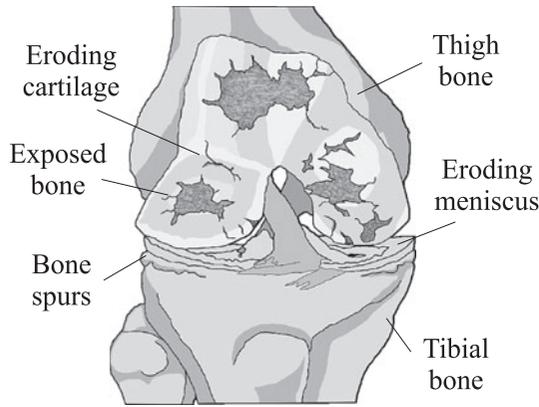


Figure 2. Illustration of knee joint with OA.

furthermore, arthropathy was found to be a major cause of the need for long-term care (third cause) or support (first cause) under the public insurance system.[10]

OA can be diagnosed using X-rays, clinical tests, magnetic resonance imaging, or arthroscopes. An arthroscope provides a more precise diagnosis of OA. However, a clinical test is useful for the early diagnosis of a patient with the initial stages of disease. In such tests, physical therapists examine symptoms such as joint stiffness, pain, synovial swelling, bony enlargement, and crepitus.[16–18]

Crepitus is one of the criteria used to understand the degree of OA. It is typically defined as an audible grinding noise and/or palpable vibrations in the joint as detected by the hand of the therapist.[14] As shown in Figure 2, crepitus is developed by roughened joint cartilages or tendons.[13] Owing to cartilage wear, damaged meniscus, and bony spurs in knee OA, the joint lubrication is lost and irregular friction or stick occurs. In addition to palpable vibrations, acoustic sounds are also developed in knee OA patients.[19,20]

3.2. Resistance model of crepitus

Because crepitus is characterized by discontinuous joint friction, we simulate its resistance pattern based on a stick-slip phenomenon model. Figure 3 shows the friction of two bodies rotating around the same axis. A rectangular imaginary object attached to a rotational spring makes contact with a shaft that rotates at $\dot{\phi}(t)$ rad/s. The angle of the shaft corresponds to that of the knee joint. We assume that Coulomb friction acts between the two bodies. The trainee experiences this frictional torque $T(t)$ N·m as a joint resistance torque. The variables involved in the model are as follows:

- J : inertia moment of the imaginary object [kg m²]
- $\theta(t)$: angle of the imaginary object [rad]
- $\phi(t)$: angle of the shaft [rad/s]
- k_r : rotary spring constant [N·m/rad]
- $T(t)$: frictional torque between two bodies [N·m]

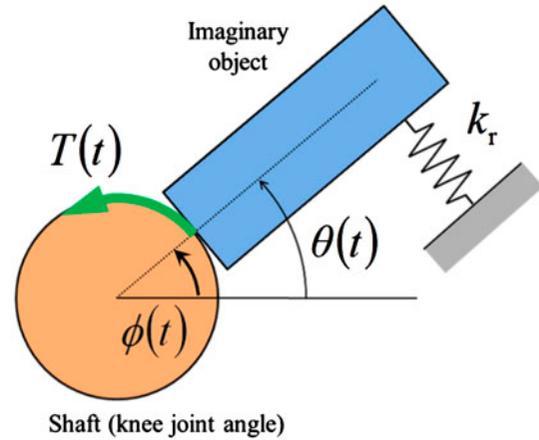


Figure 3. Stick-slip model of rotary motion.

T_k : kinetic frictional torque [N·m]

T_{smax} : maximum static frictional torque [N·m].

The stick-slip motion consists of sticking and slipping phases. Figure 4 (left) shows a schematic view of the sticking phase, in which the imaginary object rotates at the same angular velocity as the shaft, and the static frictional torque is delivered to the trainee's hand. During this phase, the torque satisfies

$$\begin{aligned} T(t) &= k_r \theta(t) \\ -T_{smax} &\leq T(t) \leq T_{smax} \end{aligned} \quad (1)$$

where T_{smax} , which is the maximum static friction, equals the maximum resistance torque presented to the trainee.

Figure 4 (right) shows the two bodies during the slipping phase. Because the two bodies are slipping, their angular velocities do not match ($\dot{\phi}(t) - \dot{\theta}(t) \neq 0$), and the angular velocity of the imaginary object is smaller than that of the shaft. The kinetic frictional torque between the two bodies is expressed as

$$T(t) = \text{sign}(\dot{\phi}(t) - \dot{\theta}(t)) \cdot T_k. \quad (2)$$

During the slipping phase, this kinetic frictional torque is presented to the trainee.

The contact status of the two bodies repetitively transfers between the sticking and the slipping phases. A condition for which the sticking phase transfers to the slipping one is that the sum of the restoring torque of the rotational spring and the inertia of the imaginary object exceeds the maximum frictional torque. This condition is expressed as

$$J\ddot{\theta}(t) + k_r \theta(t) \geq T_{smax}. \quad (3)$$

The condition for which the slipping phase transfers to the sticking one is that the angular velocity of the imaginary object reaches that of the shaft; this is expressed as

$$\dot{\theta}(t) \geq \dot{\phi}(t). \quad (4)$$

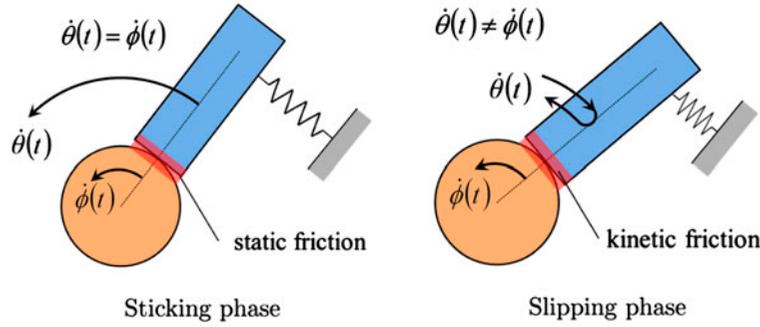


Figure 4. Two phases of friction.

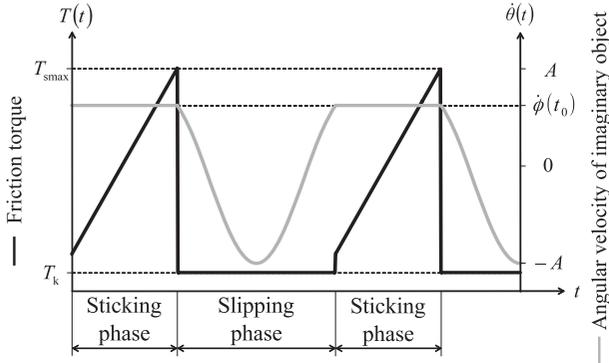


Figure 5. Schematic diagram of stick-slip motion.

When t_0 denotes the onset of slippage, the angular velocity and angle of the imaginary object at t_0 are, respectively,

$$\dot{\theta}(t_0) = \dot{\phi}(t_0), \quad (5)$$

$$\theta(t_0) = \frac{T_{smax} - J\ddot{\theta}(t_0)}{k_r}. \quad (6)$$

With (5) and (6) being the initial conditions, $\dot{\theta}(t)$ is computed as

$$\begin{aligned} \dot{\theta}(t) &= -\frac{T_{smax} - T_k}{\sqrt{Jk_r}} \sin \sqrt{\frac{k_r}{J}}t + \dot{\phi}(t_0) \cos \sqrt{\frac{k_r}{J}}t \\ &= A \cos \left(\sqrt{\frac{k_r}{J}}t + \arccos \frac{\dot{\phi}(t_0)}{A} \right), \end{aligned} \quad (7)$$

$$A = \sqrt{\frac{(T_{smax} - T_k)^2}{Jk_r} + \dot{\phi}(t_0)^2}. \quad (8)$$

Figure 5 shows a schematic of the stick-slip phenomenon. While the two phases are alternatively repeated, discontinuous friction torques are generated. In the sticking and slipping phases, the static and kinetic frictional torques are presented to the trainees, respectively. One of the factors determining the period of the slipping phase is the frequency of the imaginary object's motion. According to (7), the ratio of k_r to J affects the period of the slipping phases; Specifically, the period decreases as the ratio increases.

Furthermore, as shown in later samples, T_{smax} practically determines the period of the sticking phases. While the final period is determined by the interaction between the human hand force and the patient dummy, the sticking phases tend to increase with T_{smax} .

3.3. Example of simulated resistance torques

We implemented the above-described crepitus model into the wearable knee joint. The variables used were as follows: $J = 0.01 \text{ kg m}^2$, $k_r = 100 \text{ N}\cdot\text{m}/\text{rad}$, $T_k = 0.25 \text{ N}\cdot\text{m}$, and $T_{smax} = 0.65$ or $0.8 \text{ N}\cdot\text{m}$. These parameter sets were actually tested in the latter experiment.

Figure 6 shows samples of the angular velocity of the knee joint and exerted resistance torque when the lower thigh was manually flexed. The torque was calculated based on the force measured using a load cell (Model 1004, Teda Huntleigh) installed on the lower thigh. During the sticking phase, the resistance torque increased up to the maximum static friction torque. Owing to the increased friction, the angular velocity of the knee decreased. Conversely, during the slipping phase, the resistance torque decreased, and the knee joint motion is expedited. As a result, discontinuous frictional vibration. The difference between the two samples was in the T_{smax} value. With larger T_{smax} , the sticking phases became longer because the resistance torque took longer to satisfy the stick-to-slip transition condition.

It should be noted that there is a difference between the schematic friction torques shown in Figures 5 and 6. In Figure 5, during the slipping phase, $T(t)$ has a constant value of T_k . However, in Figure 6, owing to the dynamism of human hand and limited response of the DC motor, $T(t)$ does not have a constant value of T_k .

4. Experiment to specify parameters

Our simulated crepitus is characterized by a few parameters. Based on a subjective experiment involving practicing physical therapists, we specified parameters that realize the resistances that physical therapists experience from typical crepitus.

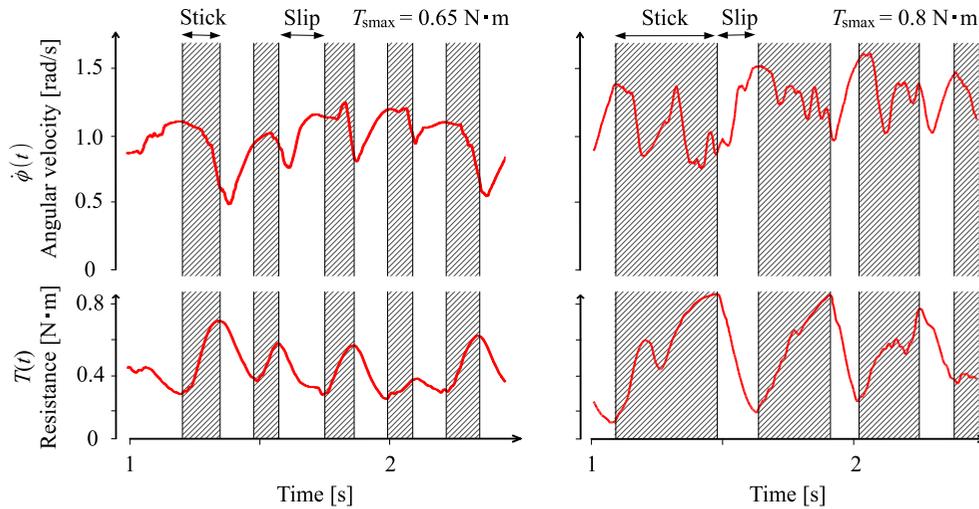


Figure 6. Examples of knee angular velocity and presented resistance torque during simulation of crepitus. Shaded areas are sticking phases.

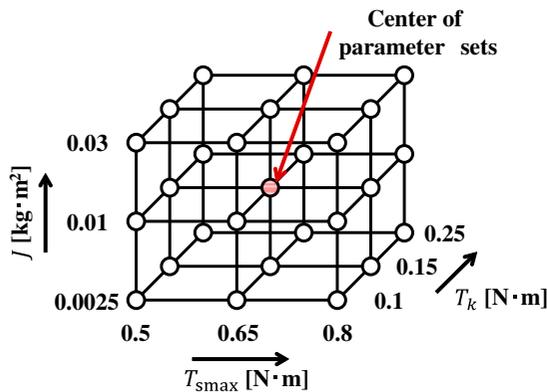


Figure 7. Combinations of parameters tested in a rating task.

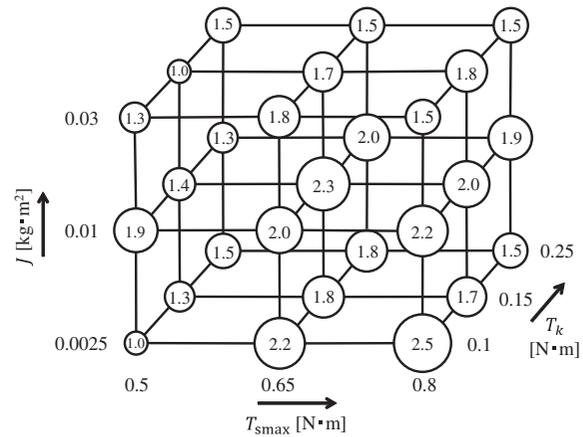


Figure 8. Result of rating task.

4.1. Parameters as stimuli

Combinations of three parameters – T_{smax} , T_k , and J – were tested in the experiment. Our crepitus model has four parameters – T_{smax} , T_k , k_r , and J . Among these parameters, T_{smax} and T_k directly influence the maximum and minimum friction torques. On the other hand, k_r and J have limited effects on the perception, although their ratio strongly influences the period of the slipping phase. Moreover, in practice, the occurrence of the stick-slip phenomenon is sensitive to a change in k_r . To vary the perceptual characters of the simulated resistances while sustaining the occurrence of the stick-slip phenomenon, it is easier to manipulate J rather than k_r . Therefore, we fixed k_r to 100 N·m/rad during the experiment.

One of the authors, who is a practicing physical therapist and did not participate in the latter experiment, carefully determined a single combination of parameters: $T_k = 0.15$, $T_{smax} = 0.65$, $J = 0.01$, and $k_r = 100$. Then, using this combination as a reference, one of T_k , T_{smax} , and J

was varied until the change in the stick-slip phenomenon became just perceivable. The set of just perceivable parameters was determined to be $T_k = \{0.1, 0.15, 0.25\}$, $T_{smax} = \{0.5, 0.65, 0.8\}$, and $J = \{0.0025, 0.01, 0.03\}$, as shown in Figure 7. Twenty-seven combinations were generated using these variables. These combinations were tested in a random order within a single set, and two sets (54 trials) were performed for individual participants.

4.2. Task

Five voluntary physical therapists—other than the authors—with experience of treating knee OA patients and clinical career of more than three years participated in the experiment. As shown in Figure 1, each grasped the lower thigh of a man wearing the knee dummy on his right leg while lying down on a bed and freely examined the knee joint resistances for a minute in each trial. The participant was

asked to rate the simulated crepitus based on the resistances felt at his/her hands. The judgment was made as follows:

- 3: I have treated patients with symptoms similar to the simulated resistances.
- 2: The simulated resistance is partly similar to that of real crepitus.
- 1: The simulated resistance is not at all similar to that of crepitus.

The participants were also allowed to use decimal numbers such as 2.5 as ratings.

4.3. Result

Figure 8 shows the average ratings of all combinations of parameters. The highest average rating was 2.5, with the standard deviation being 0.33 for $(T_k, T_{smax}, J) = (0.1, 0.8, 0.0025)$ (bottom right in the figure). The combinations neighboring this one tended to show higher ratings, and those at a distance showed lower ratings.

To investigate the effects of the parameters on the ratings, we performed a three-way ANOVA with three parameters as factors. T_{smax} had a significant impact on the ratings ($F(2, 108) = 31.6, p = 1.53E-11$). Larger T_{smax} values led to higher ratings. The sticking sense that the participants experienced became prominent with a larger T_{smax} value. Furthermore, a significant relationship was observed between the rating and J ($F(2, 108) = 11.2, p = 3.89E-5$). Specifically, the rate increased as J decreased. As described before, lower J values led to shorter slipping phases. These results suggest that the magnitude of sticking and their periods as well as the switching frequencies between the sticking and the slipping phases were major perceptual characters of crepitus. T_k did not have a statistically significant effect on the rating ($F(2, 108) = 2.29, p = .11$), in contrast to our expectation. T_k was a secondary factor affecting the quality of crepitus. This is potentially because as long as T_k is small enough compared with T_{smax} , T_k does not significantly affect the subjective quality. This may be linked to the nature of inaccurate and insensitive human perception of force during hand motion,[21] in which a resistive force of 1 N was not successfully detected during rapid hand motions.

4.4. Short discussion

In their free introspective reports, the physical therapists cited the following two points as important judgment criteria: period between sticking, and the magnitudes of the friction they felt at their hands. These two features are adjusted by T_{smax} and J , as described above. Hence, our crepitus model can be used to present the features of typical crepitus by adjusting these parameters.

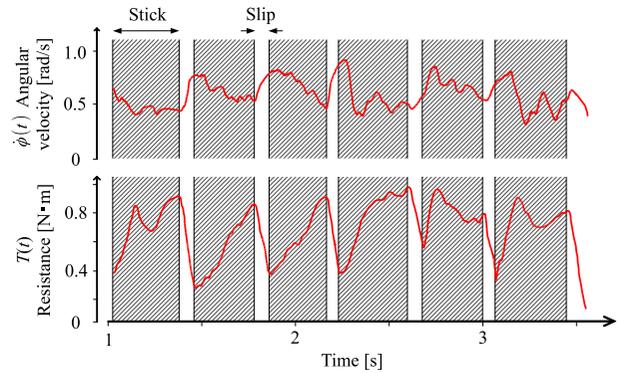


Figure 9. Sample of resistance torque and joint angular velocity with the best parameter set specified in the experiment: $(T_k, T_{smax}, J) = (0.1, 0.8, 0.0025)$.

The highest average rating was 2.5 for $(T_k, T_{smax}, J) = (0.1, 0.8, 0.0025)$. The individual ratings for the five participants were 2.5, 2.2, 3.0, 2.25, and 2.75, which means that they partly agreed that the simulated crepitus felt similar to that of OA patients. Figure 9 shows a sample of measured torques and angular velocity of the knee joint with this parameter set. Although this was a result of the dynamism of the therapist's arm and simulated crepitus, sticking was experienced approximately two times per second. These resistance torques or frequency of sticking depend on the symptoms of an individual patient; nonetheless, they were considered similar to those typically observed in clinical situations.

To improve the simulated crepitus further, flaws reported by the participants need to be considered. First, crepitus typically does not occur in the entire moving range of the knee joint; instead, it is observed only in a limited motion range. Second, crepitus during knee extension typically differs from that during knee flexion. For example, in some patients, it is often observed during flexion but rarely during extension. The implementation of such irregularities may promote the realism of simulated crepitus.

Although we specified one parameter combination, we cannot deny that there may be even better parameter sets outside the space that we examined. We informally tested another parameter set $(T_k, T_{smax}, J) = (0.1, 1.0, 0.0025)$ of which T_{smax} was larger than the one specified as best in the experiment. This parameter combination exhibited crepitus of even severer OA, indicating that it is worth exploring a wider parameter space for the better simulation of crepitus.

5. Conclusion

To help trainee physical therapists learn manual examination techniques, we have developed a wearable patient dummy that simulates the characteristic resistance forces of an impaired knee joint. Our simple and commercially feasible mechanism is expected to afford high realism

including complex human joint motions and human-like skin and bone features. We developed a model to generate the joint resistances caused by crepitus of knee OA patients. Crepitus is characterized by palpable vibrations owing to discontinuous friction of disrupted joint cartilages or bones. Our crepitus model simulates stick-slip friction considering the discontinuous frictions of roughened joint surfaces. To specify the parameters of the model, we conducted a subjective evaluation test in which practicing physical therapists rated various simulated crepitus with different parameter sets. As a result, the therapists partially agreed with the validity of a well-tuned parameter combination in terms of the similarity with clinical crepitus. Some issues remain to be resolved for better simulating crepitus. Furthermore, the parameters specified in this study need to be adjusted slightly for other dummy robots with different mechanisms. Nonetheless, the practical value of patient dummy robots has been improved by introducing simulated crepitus as an additional type of simulated symptom.

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Notes on contributors



Shun Ishikawa is a mechanical engineer who received BS and MS degrees in engineering from Nagoya University in 2011 and 2014, respectively. His study interests lie on the field of mechanical design and human perception.



Shogo Okamoto received MS and PhD degrees in information sciences in 2007 and 2010, respectively, from the Graduate School of Information Sciences, Tohoku University. Since 2010, he has been an assistant professor at the Graduate School of Engineering, Nagoya University. His research interests include haptics and human-assistive technology.



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Kaoru Isogai received a MS degree in physical and occupational therapy from Nagoya University, Japan, in 2005. He worked as a physical therapist for 24 years. From 2009, he has been a professor at the department of physical therapy, Tokoha University, Japan. He is the chairperson of Society for Surface Anatomy.



Yoji Yamada received a PhD degree from the Tokyo Institute of Technology in 1990. He has been an associate professor at the Toyota Technological Institute, Japan since 1983. In 2004, he joined the National Institute of Advanced Industrial and Science Technology (AIST), as a group leader of the Safety Intelligence Research Group at the Intelligent Systems Research Institute. In 2008, he moved to the Graduate School of Engineering, Nagoya University, as a professor.

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