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アクティブおよびパッシブ力を発生させることが可能な骨折モデルの開発

Active and passive fracture reduction force simulations using a musculoskeletal model developed with pneumatic McKibben actuators

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Abstract: A physical model of a fractured femur and its surrounding soft tissue is developed in order to simulate active and passive muscle forces during a robot assisted fracture reduction procedure. In such procedures, besides aiming for accuracy in reduction, smaller magnitude reduction forces absorbed by the surrounding soft tissue will reduce the risk of further injury to the patient and increase the chances of recovery. The developed model uses pneumatic McKibben actuators to represent the active and passive muscles. Simulation of the developed model can be compared to force simulation values from a previously developed Hill muscle model. These force simulations will be fundamental in constructing reduction paths with the least reduction force for the assistive fracture reduction robot. In addition, the developed realistic physical models will be beneficial as a tool for fracture reduction training.

Key Words: Fracture reduction force, musculoskeletal model, pneumatic muscle

1. Introduction

Fracture reduction describes the medical procedure to restore a fractured bone to its original alignment. This procedure is carried out before a fracture fixator can be inserted to fix the patient’s fracture condition. Reductions are commonly performed manually by the surgeons but drawbacks of manual reduction include there being no quantitative measure for applied forces, the excessive radiation exposure and it being physically demanding for surgeons. A robot assisted fracture reduction system is an alternative solution to these shortcomings as it minimizes human error, provides higher fracture reduction accuracy and allows a quantifiable measure of the applied force as demonstrated by our developed system(1).

One major concern with the use of surgical robots in medical procedures is patient safety. The success of a robot assisted fracture reduction procedure is commonly measured by the nonexistence of mechanical failures during the surgical procedure and the percentage of accurate restoration of the original bone alignment. However, one area that is often overlooked is the condition of the soft tissues surrounding the bone involved in the reduction procedure.

In order to understand the soft tissue response during this procedure, a physical model of the fractured femur and its surrounding soft tissue is being developed. Diaphyseal or long bone fracture of the femur is chosen to be mimicked as it has been reported to be one of the more commonly occurring fractures. Criteria for the model include matching the anatomy of the fractured limb and mimicking the response of the surrounding tissue during the fracture reduction procedure.

With the general goal of increasing the accuracy and safety of a robot assisted fracture reduction procedure, this research aims to develop physical models in order to realistically simulate forces in the surrounding soft tissue during fracture reduction. In addition, the physical models can be used as fracture reduction training tools, where they can be utilized as a platform for practice prior to performing the actual procedure on patients.

2. Prototype

2-1 Physical musculoskeletal model

A physical model of the lower limb is developed in order to mimic the muscle force response. In particular, the model aims to mimic the conditions of the bone and its surrounding soft tissue for a diaphyseal fracture of the femur.

McKibben actuators, which are a type of pneumatic artificial muscles reported to have performance similar to that of biological muscles, were used to mimic the response of the actual muscles. Previous research has shown that for actuator lengths less than resting length, the actuator provides a first order approximation of biological muscles(2). The McKibben actuator used in this study is made up of a rubber tube surrounded by a tough plastic weave, developed by the Shadow Robot Company Ltd.(3). Two different actuator lengths, 210 mm and 290 mm, were used to build this model. These actuators have the ability to contract when the inner rubber tube part of the actuator is inflated with pressurized compressed air and would otherwise be in extension.

For this preliminary model, one muscle out of each anterior, posterior, medial and lateral compartments were replicated. These representative muscles are expected to exhibit a greater response when simulated as compared to their counterparts in their respective groups, based on their biological functions. The muscles that were replicated are the rectus femoris (anterior), biceps femoris (posterior), adductor longus (medial) and iliotibial tract (lateral). In order to closely mimic the biomechanical properties of biological muscles, the insertion and origin points of the aforementioned muscles were closely mimicked. In addition, biological muscle resting lengths were also observed.

Fig. 1 Physical musculoskeletal model of a diaphyseal fracture femur

2-2 Fracture reduction simulations

Manual fracture reduction simulations were performed using the developed musculoskeletal model. The initial position of the proximal and distal fractured bone pieces were set for each trial and an orthopedic surgeon performed the fracture reduction procedure repeatedly for 7 trials. The model was covered during the trials and the surgeon performed the fracture reduction procedure guided by the previously developed navigation system(1). Reflective markers were placed on the proximal and distal bone to track the bone positions and a force sensor was attached to the handle which was connected to the surgeon's hand. This enabled a direct recording of the total amount of force applied by the surgeon to the model. Each trial was considered complete and successful when the surgeon managed to match the distal and proximal bone pieces as close as possible to its original position after a series of traction and rotation. The duration for each trial was also recorded.

Fig. 2 Initial (left) and end (right) position of the distal and proximal fractured bone pieces

The pneumatic muscles were not activated during these initial trials. Muscles were not also pre-stretched, so the resistance felt by the surgeon was solely due to the pneumatic muscles' inherent properties. Feedbacks were also acquired from the surgeon regarding the differences and similarities of performing the fracture reduction procedure on the musculoskeletal model and on an actual patient.

3. Experimental Results

Since the preliminary simulations were carried out without activating the pneumatic muscles, force resistance during the fracture reduction trials came from the passive properties of the pneumatic muscle. Force-length experiments were carried out in order to understand the passive response of the pneumatic muscles (Figure 3).

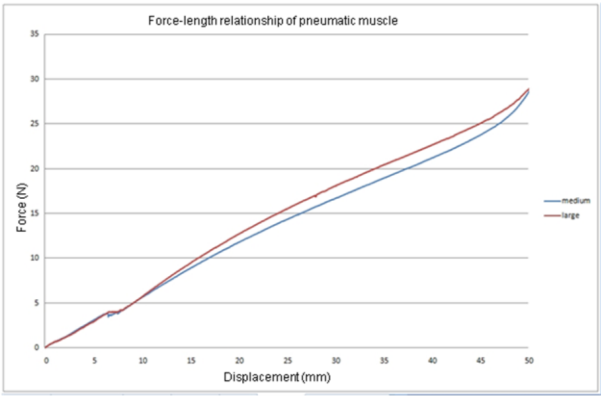

Fig. 3 Force-length relationship of the pneumatic muscles with length 210 mm (medium) and 290 mm (large)

In terms of fracture reduction force, the force applied on the musculoskeletal model showed a common progression between trials and also that with a manual reduction. Namely, the reduction force started with an increase in force where the distal fragment of the bone undergoes traction, then is rotated and the final stage shows little fluctuation in force where small adjustments is made to finalize the bone position (Figure 4).

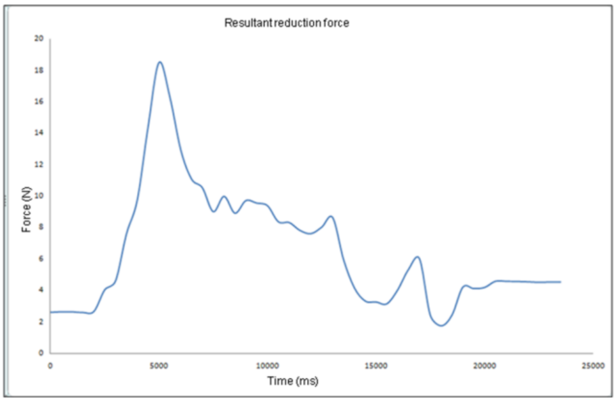

Fig. 4 Resultant reduction force for fracture reduction carried out on the bone-soft tissue model

Qualitatively, the developed musculoskeletal model has been found to produce similar resistance when compared to an actual biological environment. Additional resistance and components of soft tissue has been suggested to be added in order to further closely mimic the biomechanics of the bone-soft tissue environment, this includes the neuromuscular system.

4. Discussion

The main aim of fracture reduction procedures is to accurately reposition the fractured bone pieces into its original position. With the development of robot assisted fracture reduction systems, the accuracy and safety of the procedure is greatly improved as compared to current manual procedures. This study aims to further increase the level of safety of fracture reduction procedures performed with the robot assisted system by focusing on minimizing the fracture reduction force applied to the bone-soft tissue interaction. By minimizing the forces at the soft tissue surrounding the fracture site, additional soft tissue injuries can be avoided which leads to a better prognosis for the patient. Developing a realistic musculoskeletal model is expected help in better understanding the bone-soft tissue interaction during the fracture reduction procedure.

The current model introduces a basic bone-soft tissue model with passive force feedback. Qualitative and quantitative validations have to be carried out in order to accurately replicate the biomechanical properties of the biological system. Currently, qualitative validations come from surgeon feedbacks obtained during fracture reduction simulation trials. These feedbacks are important in improving the design of the model and this feedback-modification cycle is expected to continue throughout the design process. In order to further closely replicate biological bone-muscles interactions, a control system is currently being developed to mimic the force response of individual muscles. These force responses will then be implemented to control the pneumatic muscles active response in the musculoskeletal model. In addition, simulation of force values from individual muscle will be carried out to allow determination of fracture reduction forces from specific muscles.

The musculoskeletal model is also developed to be used as training tools for practicing surgeons and medical students alike. Since the model mimics the bone-soft tissue environment, users will be able to practice performing the fracture reduction procedure prior to performing it on an actual patient. This allows the users to familiarize themselves with the actual surrounding and learn to maneuver the system in order to minimize any possible errors during the actual procedure, hence contributing to the overall goal of increasing patient safety in robot assisted fracture reduction systems.

References

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