

Musculoskeletal model of diaphyseal fractured femur using McKibben pneumatic actuators for fracture reduction force simulations

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Introduction: Fracture reduction describes the procedure to realign a fractured bone to its original position through a series of translations and rotations of the bone fragments. This procedure is commonly done manually by the orthopaedic surgeon with the help of imaging devices but precision and the amount of applied force are factors that are difficult to control. In order to increase precision and minimize errors in conducting fracture reduction procedures, a robot assisted fracture reduction system has been developed by our group¹. This system functions to provide power assistance to the surgeon in precisely handling translation and rotation sequences. One major concern in using surgical robots in medical procedures is patient safety and with robot assisted fracture reduction procedures, the success of the procedure is commonly defined by the accuracy in realigning the bone fragments and the absence of mechanical error. However, one area that is often overlooked is the condition of the soft tissues surrounding the fracture site. Force applied during the fracture reduction procedure will also be absorbed by the surrounding soft tissue and excessive amounts of force may lead to soft tissue injuries. This study describes the development of a physical musculoskeletal model of a diaphyseal fracture of the femur using McKibben pneumatic actuators. The model aims to realistically simulate forces in the surrounding soft tissues during fracture reduction in order to increase safety and accuracy of a robot assisted fracture reduction system.

Materials & Methods: McKibben pneumatic actuators are a type of pneumatic artificial muscle which were initially used to motorize orthotic arms. The actuators used in this study were developed by the Shadow Robot Company Ltd. where it is made up of a tough plastic weave with an inflatable rubber tube as the core. The ends of the muscles are closed with one end being the air input and the other acting as a force attachment point². The actuator contracts when compressed air is supplied through it and this contraction-extension motion coupled with its resultant force is used to mimic the response of an actual muscle. For the musculoskeletal model, one muscle is chosen to represent each anterior, posterior, medial and lateral thigh compartment respectively; the rectus femoris, biceps femoris, adductor longus and iliotibial tract. These four muscles were attached to a fractured Sawbones® femur model where the attachment points closely replicated the origin and insertion points of the actual muscles³. Fracture reduction simulations were carried out using the musculoskeletal model where surgeons performed 7 fracture reduction trials repeatedly with guidance from the previously developed navigation system¹ (Figure 1(a)). Initial positions for the proximal and distal bone fragments were set for all trials and trials were considered complete when the surgeon confirms to have matched the bone fragments as close as possible to its original position after a series of translations and rotations. The position of the bone fragments were tracked via attached reflective markers and residual distance, defined as the distance between the tip of the distal and proximal bone fragments, were calculated. The amount of force applied by the surgeon during the fracture reduction procedure was recorded by a force sensor attached to a handle that was the interface between the surgeon and the model. Trial duration and the surgeon's evaluations on the model were also recorded.

Results: Residual distance: As shown in Figure 1 (b), the distance between the bone fragments decreases as the fracture reduction trial progresses. Maximum distance, recorded at the initial stage was 38.2 mm and the minimum was 1.5 mm.

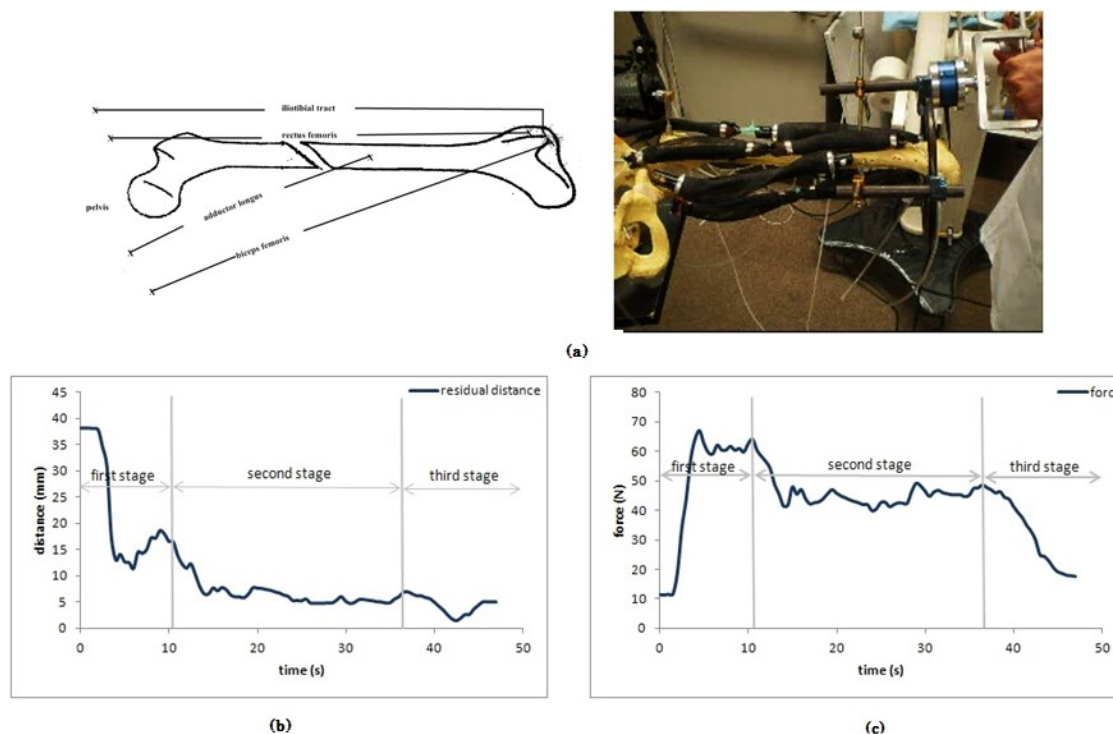


Figure 1. (a) Musculoskeletal model developed using McKibben actuators - schematic model (left), actual model (right), (b) Residual distance throughout the fracture reduction trial, (c) Force applied to the model during trial

Force: The force applied to the musculoskeletal model showed a progression that is common between trials and that of manual reduction procedures. As shown in Figure 1(c), the force path started with an increase in force where the distal fragment of the bone undergoes traction (stage 1), then is rotated (stage 2) and the final stage shows little fluctuation in force where small adjustments are made to finalize the bone position (stage 3). Maximum force recorded was 66.8N.

Discussion: When comparing the model qualitatively with an actual biological environment based on the surgeon's experiences, the model was found to produce a similar amount of resistance. However, additional resistance and components of soft tissue has been suggested to be added to further closely mimic the biomechanics of the bone-soft tissue environment. Since the current model relied on non-activated pneumatic actuators, subsequent trials will be conducted with controlled dynamic active response from the pneumatic actuators in order to increase resistance of the model to more closely replicate the fractured femur soft tissue environment. The model is developed with the aim to understand bone-soft tissue interaction in order to allow surgeons to perform robot assisted fracture reduction procedures while afflicting minimal injuries to the surrounding soft tissues. In addition, the model is also developed to be used as training tools for both practicing surgeons and medical students as with the similarity of actual 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 familiarity with the actual surrounding and allows users to 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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