ARTIFICIAL MUSCLES FOR A NOVEL SIMULATOR IN MINIMALLY INVASIVE SPINE SURGERY

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I. Introduction

The gathering of surgical skills currently is carried out in traditional or simulated environments. Training is either performed by "learning by doing" on the patient, computer based models, studies on animal or human specimen and patient simulators [1], [2]. As a new training modality and to improve patient safety in the future, a novel patient simulator is currently in development [3]. For a realistic haptic feedback, an augmented reality (AR) simulator consisting of a patient phantom and a tool tracking system was designed (see Fig 1). Novice surgeons will be able to train the needle insertion for cement augmentation techniques (CAT) with artificial tissues. The aim of this study was to find materials which provide a feedback comparable to natural muscles and skin. These synthetic tissues, which are an integral part of this simulator, should generate a high fidelity haptic feedback for surgical needle insertion and therefore should have assimilable mechanical properties to natural tissues. Suitable artificial vertebrae were already developed and validated [4], [5].

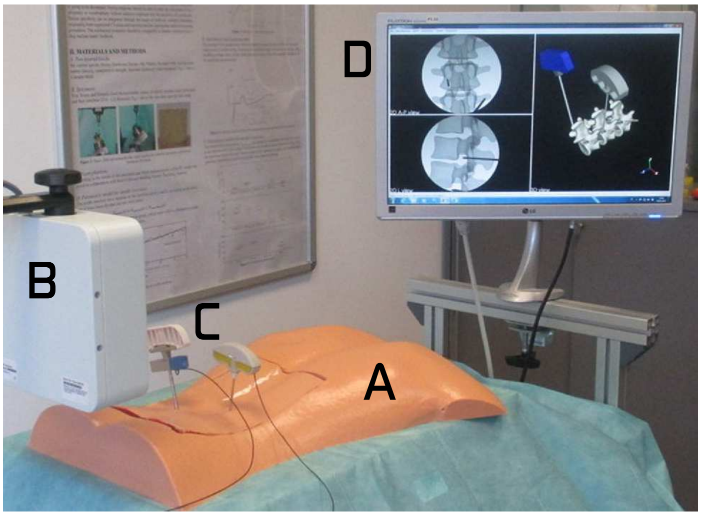

Figure 1: AR simulator for CATs consisting of a patient phantom (A), an electromagnetic tracking system (B), real instruments (C) and a computer model to simulate fluoroscopy imaging without any exposure to radiation (D)

II. Materials and Methods

A. Human specimen

For realistic human insertion data, a fresh cadaveric human spine was used (see Fig 2 A). The vertebrae were left with the testing sample to preserve muscle tension.

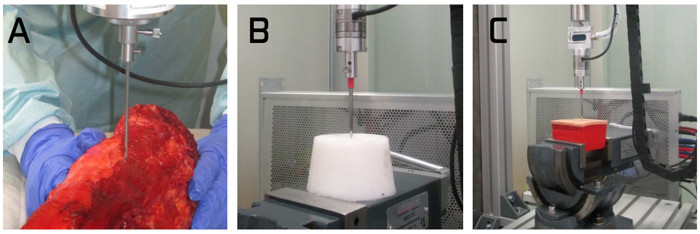

Figure 2: Insertions performed into A: human specimen, B: silicone rubber 60% SB1, C: 50% modified rubber block with red color additive and skin

B. Artificial muscle tissue blocks

To create artificial muscles, 15 silicone rubber blocks (SB, see Fig 2B) were agitated with 2 different silicone oils (SB1, SB2) in amounts of 10 to 70 (in intervals of 10) percent of whole rubber mass. To imitate fasciae, special cling films were embedded in a depth of approximately 10mm. Further, selected muscles were also fused with a red color additive to provide visual impression of muscle tissue (see Fig 2 C).

C. Insertion measurement test setting

An earlier study identified the axial insertion force as main parameter to develop artificial tissues [4]. Insertion measurements (see Fig 3) were performed in three phases: an 11 gauge diamond tip needle was inserted for 20mm with a feed rate of 10mm/s (insertion phase), stopped for 8 seconds (relaxation phase) and then removed with a feed rate of 10mm/s (extraction phase).

$$F_n(t) = \begin{cases} f_{cut} * \lambda(\Delta x(t)) * \Delta x(t) & \text{insertion \& relaxation phase} \\ F_{t,ex(t)} & \text{extraction phase} \end{cases}$$

Equation 1: The needle force $F_n(t)$ is composed by cutting and clamping forces (Δx ... insertion depth, λ ... needle geometry dependent shape function, f_{cut} ... cutting forces, $F_t(t)$ ... tissue forces)

D. Parametric model for needle insertion

Muscle tissue was modeled with a standard linear solid model yielding the tissue force $F_t(t)$. The interaction between needle and tissue is given by the needle force $F_n(t)$ (see Eq 1), which is composed by cutting and clamping forces. During insertion phase the needle force increases with insertion depth Δx. The corresponding proportional cutting coefficient is given by f_{cut}. Needle geometry is modeled by a depth-dependent shape function λ (Δx). During extraction phase, a conjoint movement of needle and tissue emerges, until a certain force threshold F_{rel} is exceeded and the needle slips out of the tissue.

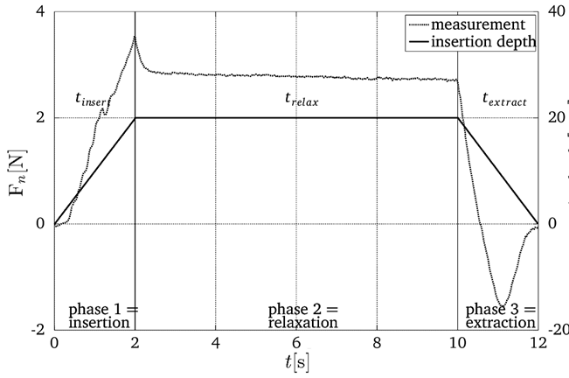

Figure 3: Insertion depth, time and needle force of measurement phases: insertion, relaxation and extraction

III. Results

A. Specimens and artificial muscle tissue blocks

Average needle forces of human specimen are 6.66N ± 3.91N (mean ± standard deviation) for the maximum insertion force, 2.48N ± 1.17N for the relaxation and -0.57N ± 0.23N for the maximum extraction force. In Fig 4 the results of the human specimen and standard deviations versus three best silicone blocks are plotted. SB1-60% and SB2-50% are the best fitting blocks according to the parametric model, SB2-50% modified block is the best according to the similarity compared to human average insertion curve. SB1-60% maximum forces are 3.22N ± 0.11N, relaxation forces are 2.69N ± 0.10N and extraction forces are -0.65N ± 0.04N, SB2-50% results are 3.26N ± 0.11N, 2.66N ± 0.05N, -1.32N ± 0.19N, and SB2-50% modified block`s measurement results are 5.64N ± 0.72N, 3.02N ± 0.39N, -1.99N ± 0.37N, respectively.

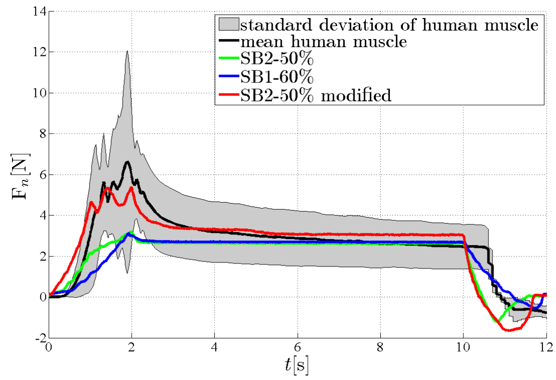

Figure 4: Mean plots for insertion measurements of best fitting silicone blocks in comparison to mean and standard deviation of human muscle

B. Parametric model for needle insertion

The characteristic parameters c_1, d/c_2 and f_{cut} were computed for all insertion measurements. The parametrical model for the needle-tissue interaction was fitted to the data with a mean relative error of 2.02% and an overall maximum error of 4.47%.

IV. Discussion

The parametric model identifies the silicone blocks SB2-50% and the SB1-60% as the most suitable natural muscle imitating materials, especially for the relaxation and cutting forces. By adding the color additive and the cling film into the SB2-50% block, the insertion force increased and the measurement curve coincide with the human muscle average (Fig 3 - SB2-50% modified). This modified block fits best to provide an appropriate haptical as well as a visual feedback. SB1 mixtures showed an oozing of the silicone oil, hence a change of the mechanical properties was visible, so SB2 blocks were integrated in the AR simulator.

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