

Measuring muscle and joint geometry parameters for a shoulder model

Mary D. Klein Breteler, Cees.W. Spoor* and Frans C.T. Van der Helm*

Institute for Fundamental and Clinical Human Movement Sciences, Department of Human Movement Sciences, Vrije Universiteit, Amsterdam, the Netherlands

*Department of Mechanical Engineering and Marine Technology, Technische Universiteit Delft, The Netherlands

ABSTRACT - An extensive set of muscle and joint geometry parameters is measured on the right shoulder of an embalmed male. The parameter set is needed to enhance the accuracy of muscle and joint modelling of the shoulder. From the measured parameters, model parameters were calculated for a computer model of the shoulder, developed at the Man-Machine Systems Group of the Laboratory of Measurement and Control at the Delft University of Technology. With the computer model an abduction of the arm was simulated in steps of 30°. In each of the simulated arm positions, actual sarcomere length was calculated from the muscle length (which is, among others, output of the model). A curve representing the sarcomere force-length relationship indicates the maximum force that all muscle parts can exert in each position. For most muscle parts it could be seen that the complete movement (the simulated abduction) takes place within the range in which force can be exerted. Muscle parts act on the ascending limb as well as on the plateau and on the descending limb. The measurements resulted in a very complete dataset that is not only important for the refinement of the shoulder model, but also for functional analyses of shoulder movements in general.

INTRODUCTION

To study the complex movements of the shoulder mechanism a computer model is developed at the Man Machine Systems group of the Laboratory for Measurement and Control at the Delft University of Technology (Pronk, 1991; Van der Helm, 1991). A description of the shoulder model is given elsewhere in these Proceedings by Van der Helm.

Output of the shoulder model are: orientations of the bones, muscle lengths, muscle force vectors, moment arms and muscle and joint moments. The issue of importance for this paper is the calculation of muscle forces by the model. Since there are more muscle parts than degrees of freedom, muscle forces have to be calculated with an optimization procedure. The current procedure minimizes the sum of squared muscle stresses in the entire system. The criterion for activation (or not) of a muscle part is not only a favorable moment arm. Also, the maximum force of a muscle part, at maximum activation, is of importance. Obviously, the maximum force depends, apart from the physiological cross-section, on the relative length of a muscle. However, this length cannot be calculated without additional muscle parameters.

The main purpose of this research is to measure sufficient muscle geometry parameters so that optimum muscle length can be added as a model parameter for the shoulder model. The most important parameters that are additionally measured in this research are sarcomere length and muscle fiber

length. Because these lengths have to be compatible with the dimensions of the cadaver, a whole new set of parameters had to be measured.

From the measured cadaver parameters, model parameters were calculated. After implementation of the model parameters an abduction of the arm was simulated. Relative muscle lengths during the abduction were calculated.

METHODS

Measurements were performed on the right shoulder of the cadaver of a 57-year-old muscular man. The cadaver was fixed to a stainless steel frame, so the cadaver could be easily put upright.

In every segment of the skeleton, i.e. the head, thorax, clavicle, scapula, humerus, radius and ulna, four or five screws were driven. These screws were distributed over the bone in such a way that they could be used as reference points for measuring

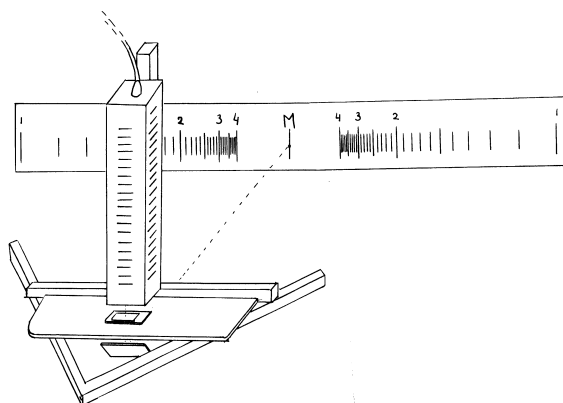


Figure 1- The laser diffraction line-up.

changes in position and orientation. Before the dissection was started, the positions of sixteen palpable bony structures and of all reference screws were measured. The positions of the skeletal parts as determined in this measurement were used as standard body posture. For measurement of positions the palpator was used (Pronk & Van der Helm, 1991). The skin and all the fatty tissues over and between the muscles was removed. Every muscle was cleared from its surrounding without disconnecting the origo or insertion. For every muscle it was decided in how many parts it was to be divided. Criteria were: attachment sites on different parts of the skeleton, differences in muscle fiber length, differences in the angles between muscle fibers and bones, attachments to another tendon plate or already present gliding planes between parts of the

muscle. For every muscle part the beginning and end of an estimated mean muscle fiber were marked. A numbered label was attached to the bone and another onto the muscle. For every attachment site it was noted which labels belonged to which muscle part. After all muscles had been removed from the cadaver and positions of origos and insertions of all ligaments had been measured, the ligaments were cut. After the bones were separated, joint surfaces, reference screws and attachment sites of all muscle parts were digitized. The length of each muscle part was measured with the help of a string and a ruler. The string was laid tightly along the muscle and held at the positions of the labels that marked the beginning and end of the muscle part. This length was measured with a ruler. The muscle had to be laid down on a flat sur-

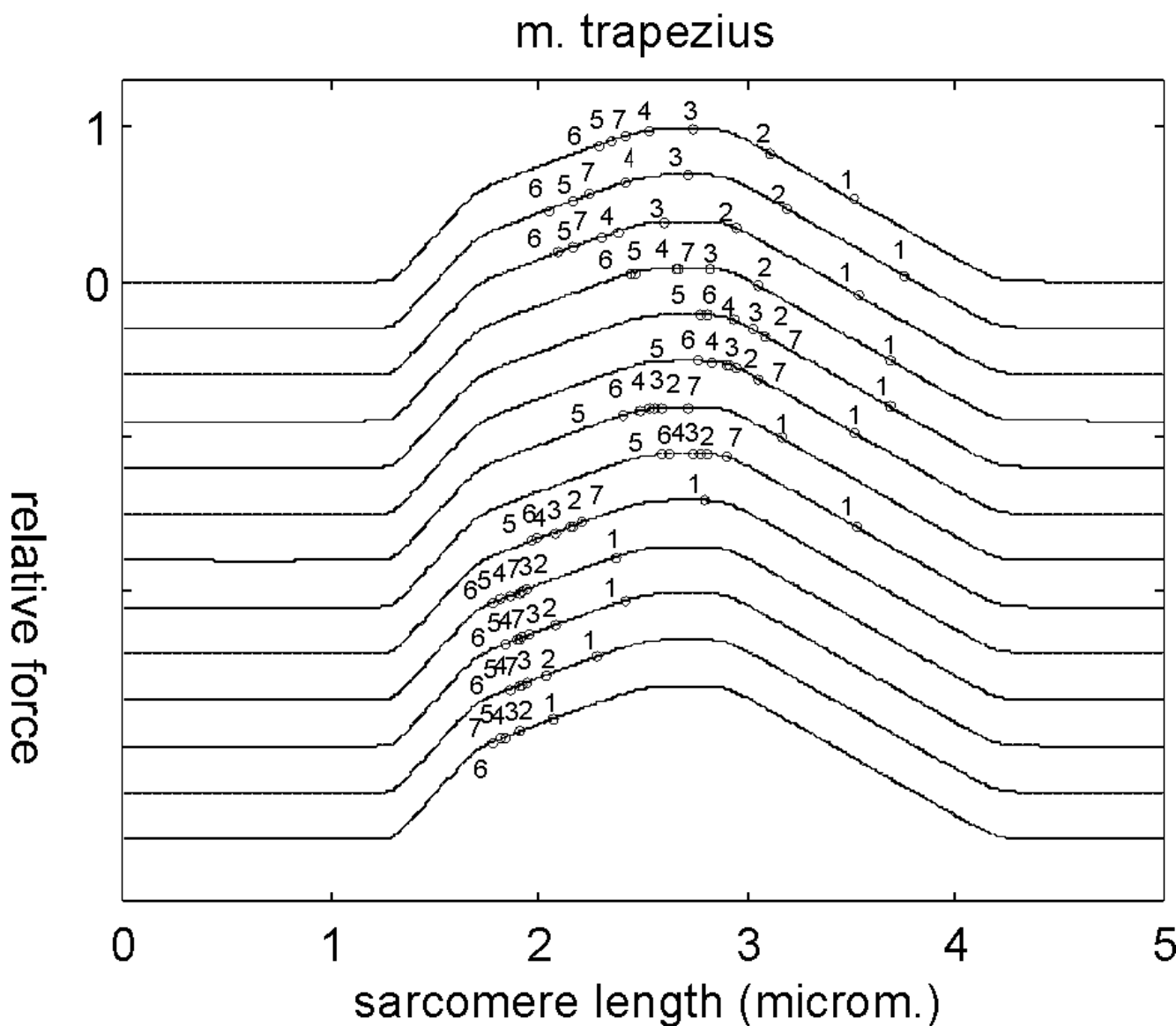


Figure 2- Maximal force of the m.trapezius during abduction. For an explanation, see the text.

face first, because some muscles were rumpled or ran over a curved surface.

From every muscle part, three fiber bundles were taken of approximately 2 mm wide. The bundles were representative for that muscle part. If, for example, a muscle part consisted of long and some shorter muscle fibers, two long and one short bundle was taken. Of each bundle the length was determined with a ruler. The mean length of these bundles was considered to be the fiber length of that muscle part.

Because of the striated character of skeleton muscles the sarcomere length can be measured by laser diffraction. A small part of a muscle fiber is regarded as a lattice, which causes a laser bundle to create a diffraction pattern on a screen. The laser tube was positioned in a fixed distance from the wall. To be able to directly read the sarcomere length a scale was painted on the wall.

A vertical laser tube is mounted on a frame. Below the laser tube is a horizontal metal stage to support slides with muscle samples. The laser light passes through a hole in the stage, reflects in a 45°-mirror and is projected onto a scale on the wall.

data processing

Data are expressed in a global orthogonal coordinate system. The x-axis points laterally, perpendicular to a plane through (IJ), (PX), T8 and C7. The z-axis points upwards from the middle between PX and T8 towards the middle between IJ and C7, and the y-axis points forwards, perpendicular to the x- and z-axes.

The number of sarcomeres in a bundle is calculated by dividing the bundle length by the mean sarcomere length in that bundle. Optimum bundle length is obtained by multiplying the number of sarcomeres with the optimum sarcomere length of 2.7 μm (as measured by Walker & Schrodt (1974)). Optimum fiber length of a muscle part is the mean optimum bundle length of three bundles.

The calculations of the physiological cross-sections are based on the fact that the volume of a muscle remains constant. Of all muscle parts the mass of the muscle belly without the tendon was determined. The mass of all the labels that were still attached to the muscle part was subtracted from it. The volume of each muscle part was calculated by multiplying the mass of the muscle part with the specific gravity of muscle tissue, which was determined with an submerging experiment. The physiological cross-section is calculated by dividing the volume of each muscle part by its optimum fiber length.

Simulations

An abduction of the arm was simulated. Input were mean coordinates, rotations and forces as measured on ten living subjects (experiments by Van der Helm, 1991). Only static postures were simulated. Seven postures were simulated, one every 30° of abduction. At position 1 the arm is down and at position 7 the arm is raised in total abduction.

Output of the shoulder model is, among others, muscle length at every position. With the knowledge of optimum fiber length and tendon length, which is assumed to be a fixed length, the maximal possible force per muscle part can be calculated for every position of the arm, based on to the force-length relationship.

RESULTS AND DISCUSSION

Due to space limitations only the maximal possible forces for all seven positions during abduction for all muscle parts of the m. deltoideus and the m. trapezius are presented. The maximal force output of a muscle part depends on its length. Maximal force output is the force that a muscle can exert at a given length with maximal activation.

Figure 2 represents the maximal forces of all parts of the m. trapezius during an abduction. The solid lines represent the force-length curves of all muscle parts, which are placed above each other for ease of comparison. The x-axis gives the mean length of the sarcomeres (in μm) of a muscle part and the y-axis, which is only valid for the top muscle part, gives the relative force that a muscle part can exert, ranging between 0 and 1. The numbers 1 till 7 denote the position during the abduction. Position 1 is with the arm down and position 7 is with the arm raised. It can be seen that all numbers are positioned at the raised part of the force-length curve, which means that all muscle parts can exert force during the complete range of abduction. All muscle parts of the m. trapezius shorten during the first 6 positions and lengthen for the last position. This means that for the first six positions of the abduction all muscle parts can actively contribute to the abduction. The pattern is not equal for all muscle parts, but a wave-form is followed for adjoining muscle parts. The middle part of the m. trapezius (pars transversum) has longer sarcomeres than the upper (pars descendens) and lower (pars ascendens) parts. This points at a sarcomere length distribution, which could be very useful in enlarging the range in which force can be exerted by a muscle.

Figure 3 is the same figure as Figure 2, but for the m. deltoideus. The striking feature of this muscle is that at position 5 and higher, most muscle parts

are too short to exert any force at all. This means that, from position 5 till 7, another muscle is needed to lift the arm, for example the clavicular parts of the m. deltoideus, or the clavicular and some cranial thoracal parts of the m. pectoralis major which pass cranial from the glenohumeral rotation center at position 5 and higher. According to Herring et al. (1984), a muscle can be assumed at optimum length at the position in which the muscle is activated most. Since optimum muscle length did not take place at the same abduction position for all muscles and even muscle parts, it can be inferred that some muscles are more active in the beginning of the abduction and some muscles

are more active later in the abduction. This is most likely caused by the fact that relative moment arms of those muscles change during abduction.

CONCLUSIONS

- A complete set of parameters of the right shoulder of a cadaver is measured.
- Because optimum muscle length is known, a force-length curve can be constructed for every muscle part.
- With the force-length curve, the maximum force of a muscle part can be calculated at any position of the arm.

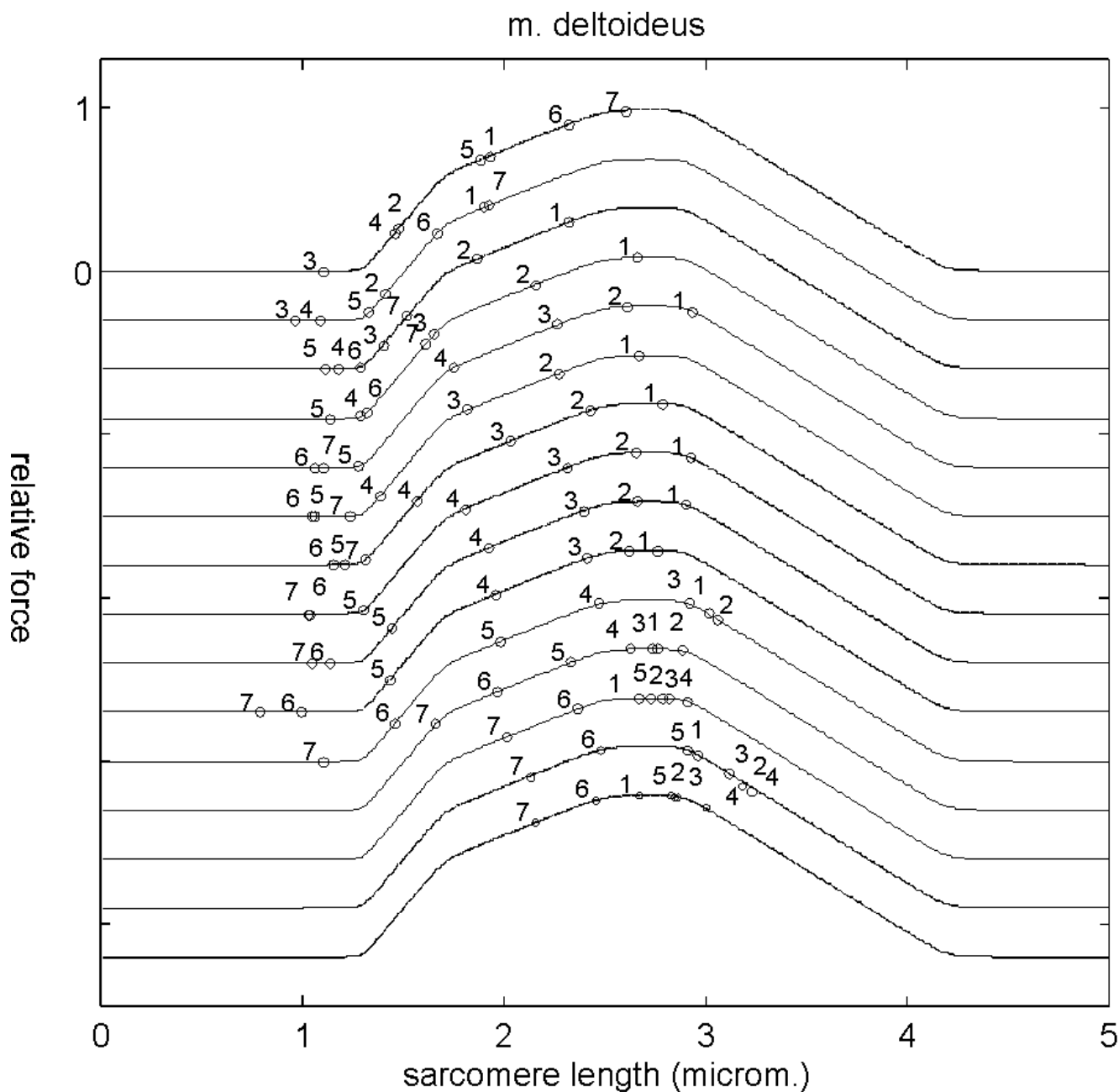


Figure 3-Maximal forces of m. deltoideus during abduction. For an explanation, see the text.

ACKNOWLEDGMENT

The authors wish to thank the Laboratory for Anatomy in Leiden for offering the facilities to conduct the cadaver experiments.

REFERENCES

- Herring S.W., Grimm A.F. and Grimm B.R. (1984). Regulation of sarcomere number in skeletal muscle: a comparison of hypotheses. *Muscle & Nerve* 7: 161-173.
- Pronk G.M. and Van der Helm F.C.T. (1991). The palpator: an instrument for measuring the positions of bones in three dimensions. *J. of Medical Engineering & Technology* 15(1): 15-20.
- Van der Helm F.C.T. (1994). Analysis of the kinematic and dynamic behavior of the shoulder mechanism. *J. of Biomechanics* 27(5): 527-550.
- Walker S.M. & Schrodt G.R. (1974). I segment lengths and thin filament periods in skeletal muscle fibres of the rhesus monkey and the human. *Anatomical Record*, 178:63-82.