DOI 10.1007/s10527-017-9643-5
Biomedical Engineering, Vol. 50, No. 5, January, 2017, pp. 305-309. Translated from Meditsinskaya Tekhnika, Vol. 50, No. 5, Sep.-Oct., 2016, pp. 12-15.
Original article submitted July 28, 2016.

Effects of Arm Prosthesis Socket Design on Pressure Distribution on the Inner Surface of the Socket

Yu. I. Zamilatskii*, S. F. Kurdibaylo, and R. R. Gainullina

Biomechanical studies of the distribution of specific pressure across the internal surface of the socket were performed, focusing on the end of the arm stump during manipulation of the prosthesis. This was undertaken using a matrix of tensometric multisensory probes. These studies showed that peak loadings at local zones decreased significantly with increases in the area and continuity of contact of the skin of the stump with the internal surface of the socket. The best results were obtained using combined sockets made from silicone.

Introduction

The complex rehabilitation of invalids with musculoskeletal injuries is a difficult and multifaceted problem. The greatest difficulties are encountered in the rehabilitation and recuperative treatment of invalids who have undergone limb amputations. It is well known that during human phylogeny the upper limb underwent extremely specific development and achieved a perfection of function and anatomical structure.

The upper limb consists of three segments: the arm, the forearm, and the hand – and has 27 degrees of freedom with respect to the shoulder girdle. From the biomechanics point of view, the upper limb consists of an open biokinematic circuit fitted with kinematic pairs. Twenty degrees of freedom apply at the joints of the hand, two at the elbow and radioulnar joints, and two at the radiocarpal joints. Thus, amputation at the level of the arm leaves just three degrees of freedom, sharply limiting the patient's movement capacity and making him or her dependent on assistance from others [1].

Amputation of one or both upper limbs at the proximal level is a powerful emotional and physical stress factor for a person. The consequence of amputation is that virtually all the body's functional systems undergo changes. Major alterations occur in relation to the musculoskeletal system; in particular, there are extensive changes to posture, with upward and anterior displacement of the shoulder girdle and the development of scapular winging. Muscle strength in the stump and shoulder girdle decreases, contractures form, and stiffness develops in the shoulder joint; various changes affecting the respiratory system also occur.

Currently the most effective means of restoring or compensating for the lost functions of the upper limb consists of prosthetization [2, 3]. In practice, prosthetization makes wide use of cosmetic, functional-cosmetic, and mechanical prostheses with a traction control system, working prostheses, and prostheses with external power sources [3]. In designing a prosthesis, regardless of the control principles and its functional significance, the main element is the socket, whose manufacturing quality and correspondence to the anatomical-morphological characteristics of the stump largely determine the capacity and convenience of use of prostheses during use. One of the key points in making the prosthesis is production of the socket [4].

Objective assessment of the effectiveness of use of arm prostheses with different socket designs was sought by performing biomechanical assessments whilst in use.

The study task was to investigate the distribution of specific pressure across the internal surface of the stumps of different designs, focusing on the end region and on areas where patients noted discomfort or pain during manipulation of their arm prostheses.

St. Petersburg G. A. Albrecht Scientific and Practical Center for Medical and Social Expertise, Prosthetics and Rehabilitation, Ministry of Labor and Social Protection of the Russian Federation, St. Petersburg, Russia; E-mail: reabin@center-albreht.ru
* To whom correspondence should be addressed.

Materials and Methods

A total of 23 male and five female patients (aged 18-45 years) took part in the study; patients had undergone amputation due to trauma, had no musculoskeletal diseases, and had no restriction to mobility in the remaining joints of the amputated limb, and who had undergone prosthetization and had been trained in use of their prostheses.

Some patients had cutaneous scarring on their arm stumps, located on the distal parts and ends.

Prosthetic sockets were made of high-pressure polyethylene sheet of thickness 3 mm, as three versions: the standard design (version 1), a full-contact version (version 2), and a combined socket with Silpen organic silicon poured directly into the socket forming a coating on the end of the stump as a layer of thickness 3-5 mm, accurately reflecting the shape of the distal part and, after polymerization, having elastic cushioning properties and high adhesiveness with the skin (version 3).

In each individual case, prostheses were initially issued for trial periods of 1-2 days, after which preliminary evaluation of prosthesis functionality and clinical examination of stumps were performed to exclude any effects of defects and prosthetization errors.

Biomechanical studies of pressure topography dynamics within sockets were performed using the programmable F-Socket system. This includes a matrix of pressure probes in the form of tensometric plates 0.2 mm thick. A cable connection was used to transfer measurement results to a computer for processing. Study results were displayed on a monitor as pressure topology plots and center of pressure trajectories, i.e., “loading lines,” and plots of the total pressure on the measuring devices.

TABLE 1. List and Description of Functional Tests for Measurement of Loading Levels and Upper Limb Stump Comfort

No.	Test name	Description of functional test
1	Resting measurement	Measurement of total loading on stump at rest
3	Maximum abduction	Measurement of peak loadings and determination of their locations during maximum abduction of the stump bearing the prosthesis
4	Load manipulation	Measurement of peak loadings and determination of their locations during holding and lifting a 3-kg load
5	Impulse loading	Measurement of peak loadings and determination of their locations while working with the “hammer” attachment

With the aim of obtaining the best connection with the stump, plates were initially cut into strips, without altering their functionality.

Multisensor probes were attached with transparent sticky tape to the end of the arm stump, with the greatest coverage at the end of the stump and zones where patients noted discomfort or pain. When socket problems were identified, devices were sent for further adjustment to prevent distortion of the final biomechanical study results.

The study protocol included a series of functional tests (Table 1) to determine the total specific pressure on the arm stump, the size of the area of contact during manipulations, and the peak loading on the support parts of the stump for the different socket versions.

Results

Measurements of resting pressure (using a prosthesis with a working attachment weighing 1800 g) gave a mean stump surface pressure for the prosthesis with the standard socket of no greater than 300 g/cm^2 with a contact area of 80 cm^2 and minor localized zones of overloading with pressures of up to 1400 g/cm^2. Pressures for the full-contact socket were similar – around 280 g/cm^2 – with minor localized zones of overloading with pressures of up to 1200 g/cm^2 and total contact areas of up to 95 cm^2. In the case of the combined socket, pressures reached 500 g/cm^2 with contact areas of up to 110 cm^2 and local overloading of up to 1000 g/cm^2 at the end of the stump (Fig. 1).

Thus, the greatest mean resting pressure (500 g/cm^2) was recorded in the prosthesis with the combined socket, though because of the greater area of contact – by up to 30 cm^2 – which was 28% greater than the area of contact of the standard socket, peak pressure bursts at the end of the stump decreased by 400 g/cm^2 as compared with the standard socket and by 200 g/cm^2 compared with the full-contact socket.

Maximum abduction of the shoulder joint produced the following mean pressure levels on the stump: up to 1000 g/cm^2 for the standard socket, a mean of 1300 g/cm^2 for the full-contact socket, and up to 1350 g/cm^2 for the combined socket (Fig. 2). However, as in the previous case, it should be noted that the peak pressure on stump ends was significantly lower for the combined socket, reaching up to 1400 g/cm^2, as compared with the other sockets, where local loadings on the end were at least 2000 g/cm^2.

The process of lifting a load was characterized by high pressures on stump ends. Stump end pressures for

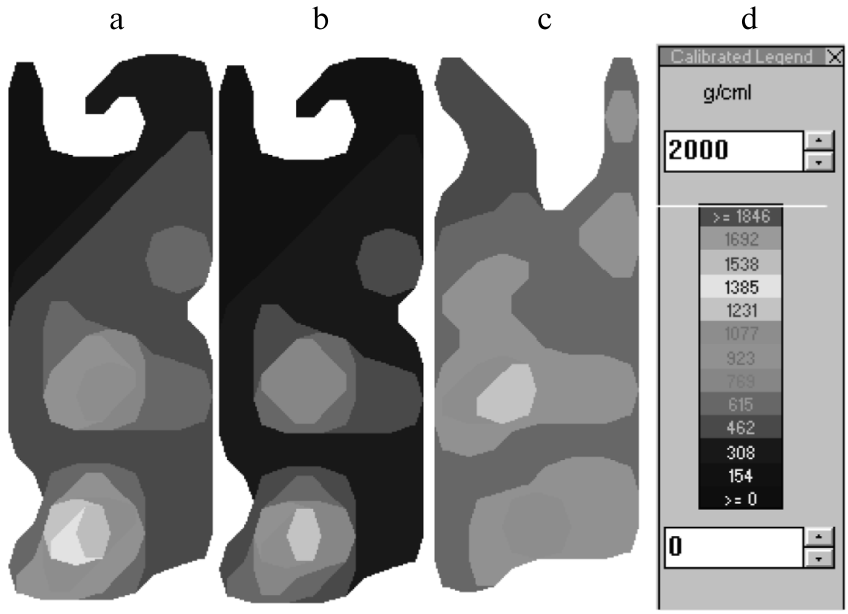

Fig. 1. Distributions of specific pressure on arm stumps at rest: a) standard socket; b) full-contact socket; c) combined socket; d) pressure map color calibration.

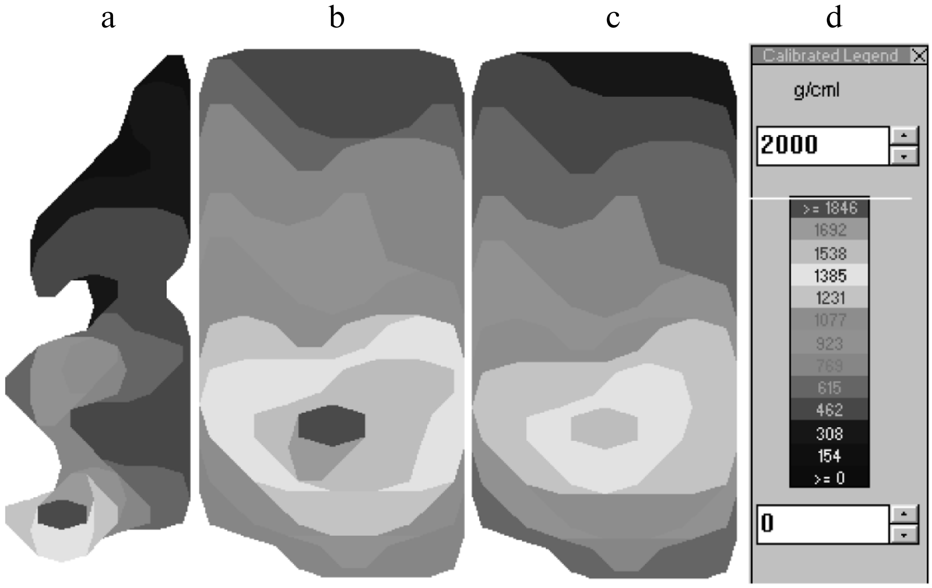

Fig. 2. Distributions of specific pressure on arm stumps on abduction: a) standard socket; b) full-contact socket; c) combined socket; d) pressure map color calibration.

the standard and full-contact sockets averaged more than 4000 g/cm^2, with peak pressures at some points exceeding 11,500 g/cm^2 (Fig. 3). These ultrahigh loadings are not seen even in lower limb prostheses during active walking, where kinetic mass at the peak of the support reaction can reach up to 150% of the patient's body weight.

In the prosthesis with the combined socket, load lifting was performed with a working pressure of up to 3000 g/cm^2 and peaks of up to 6000 g/cm^2 at stump ends,

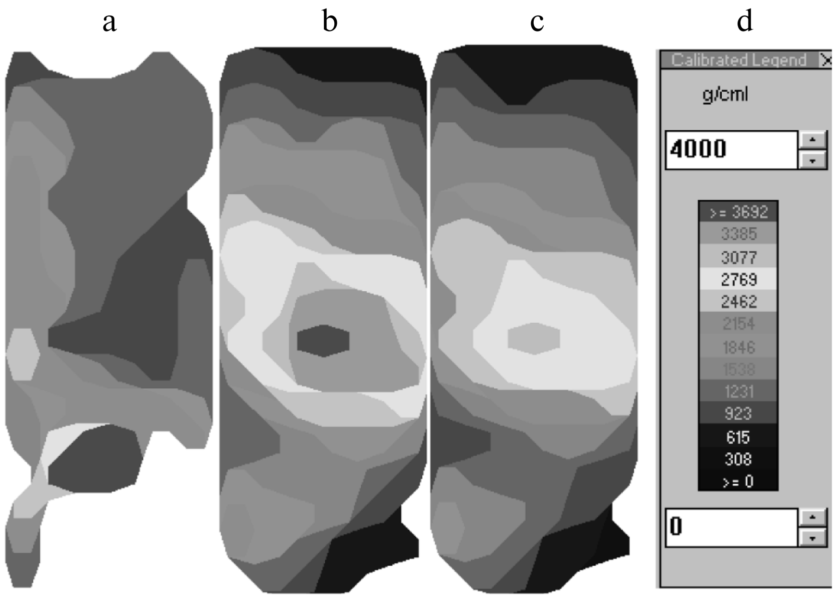

Fig. 3. Distributions of specific pressure on arm stumps on lifting a 3-kg load to a height of 1.5 m: a) standard socket; b) full-contact socket; c) combined socket; d) pressure map color calibration.

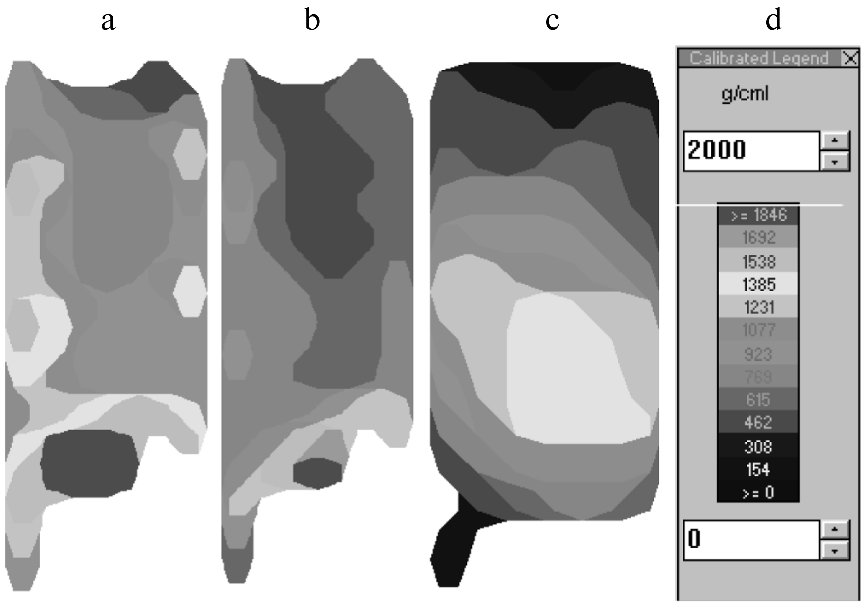

Fig. 4. Distributions of specific pressure on arm stumps on impulse loading: a) standard socket; b) full-contact socket; c) combined socket; d) pressure map color calibration.

which was also determined by the quite high areas of contact between stump ends and socket walls (up to 130 cm^2) on the background of the high adhesive properties of Silpen with the skin.

The extent of peak loading in the prosthesis with the combined socket was significantly lower than with the other sockets. Thus, as compared with the standard socket, there was a 25-30% decrease in pressure with good subjective assessments of comfort levels by patients.

A simplified impulse loading test (operating with a hammer-type attachment) was performed because of the difficulty of accurately controlling operation of arm prostheses. For recording purposes, the test was performed once with each socket, and the patient was asked to hit a nail partially inserted into a wooden plank as hard as possible four times.

This analysis showed (Fig. 4) that specific pressure on impulse loading did not exceed a mean pressure of 1600 g/cm^2 for any socket type. In the cases of the standard and full-contact sockets, clear areas of peak loading were seen in the projection of the end of the stump, with pressures of up to 2000 g/cm^2. For the combined socket, pressure was 1500 g/cm^2, without the peak pressure jump at the end of the socket characteristic of the other sockets.

Peak pressure for this socket type was 45% lower than with the standard socket and up to 30% lower than the loading level seen with the full-contact socket.

Conclusions

This is the first report of quantitative analysis of specific pressures on arm stumps with different socket designs during prosthesis utilization.

Biomechanical investigations using the programmable F-Socket system showed that the decrease in peak stump pressure in local areas using combined full-contact silicone sockets was by 45% compared with the standard socket and up to 30% compared with loading identified for the full-contact socket. The areas of stump contact with the inner surface of the socket increased by up to 30% on the background of high adhesiveness between Silpen and the skin.

Combined full-contact sockets provide for reliable fixation of the prosthesis with a minimum of piston-type movement, which enhances feedback sensations on use of working and active prostheses with a traction control system.

Improved technology has been introduced into the practice of prosthetization at a number of orthopedic prosthesis makers in Russia and there is evidence of significant improvements in the functionality of prostheses using individual combined full-contact sockets for arm prostheses made with consideration of the anatomical-functional characteristics of the limb amputation.

The main result of using combined full-contact sockets can be regarded as one stage in medical rehabilitation. Increases in quality of life open up new perspectives for return to occupational activities, adaptation, and integration of invalids into contemporary society.

REFERENCES

1. Keier A.N., Rozhkov A.V., In: Keier A.N., Rozhkov A.V. (eds.) Guidelines for Prosthetics and Orthotics [in Russian], Krismas, St. Petersburg (1999).
2. Kurdibaylo S.F., Zamilatskii Yu.I., Andrievskaya A.O., et al., in: Kurdibaylo S.F. (ed.) Technical Approaches to the Rehabilitation of Patients and Invalids with Upper Limb Lesions [in Russian], Znak, St. Petersburg (2013).
3. Kurdibaylo S.F., Zamilatskii Yu.I., Andrievskaya A.O., et al., in: Kurdibaylo S.F., Zamilatskii Yu.I., Andrievskaya A.O. (eds.) Construction of Upper Limb Prostheses (A Historical Perspective) [in Russian], Nimfa, St. Petersburg (2009).
4. Petrov V.G., Zamilatskii Yu.I., Burov G.N., et al., in: Burov G.N. (ed.) Technologies for the Manufacture of Upper Limb Prostheses [in Russian], Gippokrat, St. Petersburg (2008).