EXPERIMENTAL RECOGNITION OF LOADING CHARACTER OF TRANSTIBIAL PROSTHESIS

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This paper deals with experimental simulation of mechanical properties of transtibial prosthesis. Artificial limb allows patient standing and moving without of using others supporting devices. Therefore, patient returns back to common and active life. Design and prosthesis properties decide about comfort, safeness and reliability of prosthesis. The article summarizes a conclusion of preliminary experiment, which was performed to measurement procedure of prosthesis strain (for real loading of straight walking, downhill walking and downstairs walking and data processing.

Key words: *transtibial prosthesis, strain gauge, loading character of prosthesis*

1. Introduction

The human body replacements, especially artificial limbs, enable handicapped re-entry into common and active life and integration to the community. The prosthesis doesn't support only function of physical limb replacement, but it support social and cosmetic status as well. The most common group of replacements is artificial limbs. Lower extremity prosthesis is defined as device that substitutes missing part or nondeveloped limbs, eventually whole limb (according to ISO 8549). The prosthesis is designed according to particular requirements of a patient with a reference to its clinical status. Connection of a user and the prosthesis creates a biomechanical system. Design of artificial limb is defined by the patient activity level: physical and psychical capabilities, profession, user's workspace etc. The aim of the replacement of missing limbs is to ensure patient a support for standing and movement without using of others supporting devices.

Artificial limb consists of two basic parts: a socket and a prosthesis periphery (fig. 1) [1]. The socket designates prosthesis comfort; the periphery designates mechanical properties of the prosthesis. Indication and prosthesis design comes out from narrow cooperation of the patient, doctor who applies the artificial limb and prosthetist that assembles the prosthesis and physiotherapist that helps amputee to use prosthesis. Without communication among individual cooperative persons it is impossible to expect subjectively and objectively good workable and functionally suitable result.

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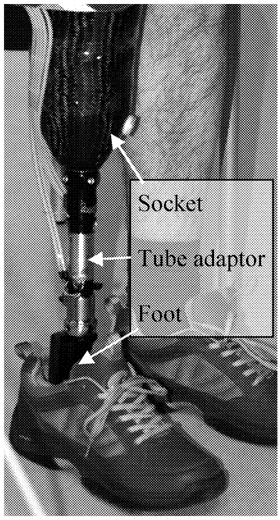

Fig.1: Transtibial prosthesis

Considerable expansion of the prosthetics was reached 'thanks to' campaigns and wars. Quantity of amputations reached several hundreds during one war day. Current prostheses are used not only as the result of war severities, but also after accident, complicated disease (e.g. diabetes, infection, tumors) or instead nondeveloped limbs and defects. Historical development of the prosthetics is rather long and noteworthy. Therefore, a historical summary is shown in following section.

2. Historical overview

2.1. Amputation

Amputation was practiced thousand years ago. Archaeological discoveries have even shown the proclaim amputation performed on Neolithic and Neanderthal man [2]. The amputations were also practised by Australian aborigines. In Peru, drawings have been founded that showing amputated limbs and certain kind of the prosthesis [3]. Invention of gunpowder had a significant effect on amputation evolution. It started with using guns, cannons and finally to battlefield amputation. At the beginning of the eighteenth century, surgeon of Napoleon Bonaparte (Baron Dominique-Jean Larrey) practiced about 200 amputations during one battlefield day (approximately one every 7 minutes) [3]. We may remind several well known names that have been associated with the battle surgery: Ambroise Paré [4], Hans von Gerssdorff, John Hunter, Robert Liston [3], Nikolai Ivanovich Pirogov and others. One of the most famous surgeons was Lisfranc (1790–1847). He was able to amputate a foot in less than 1 minute [2]. The mortality rates due to sepsis for transtibial amputation were 50 %.

2.2. Artificial leg evolution

Artificial legs are described in Indian literature as early as 1500 BC. The earliest historical record of the prosthesis comes from Herodotus (485–245 BC), who described an individual prisoner by Sparta who obtained a knife and performed an amputation of his foot. He was then able to escape from the stocks. First prosthesis could be thought artificial limb found in the ruins of Pompeii 300 BC [2].

Aforesaid Ambroise Paré (1510–1590) established technical standard for amputations in the late 1500s [2]. Design of his artificial limb was used by French armour. The concept of peg-leg was similar to modern prosthesis. Dutch surgeon Verduin constructed transtibial prosthesis with a cooper socket, a leather thigh corset and wooden foot. This prosthesis was ancestor of the thigh corset [2].

James Edward Hanger (1843–1919) sustained an amputation while serving in the Confederate army, placed rubber bumpers in solid feet and thus produced the first articulated prosthetic foot [2]. After losing his leg in the first land battle of the war, he founded the J. E. Hanger Company for development of artificial limbs in 1861 (today Hanger Orthopedic Group, Inc).

After World War I, in the United Kingdom, the Limb Fitting Centre at Queen Mary's Hospital, Roehampton, became a primer development and supply center to military veterans.

3. Statement of problem

Mechanical behavior of prosthesis depends especially on the peripheral part. Spatial arrangement of prothesis and its design influence resulting functional effect on patient. Design has to enable wide utilization, comfort, safety and reliability as much as possible. Correct function of prosthesis is further affected by alignment and adjustment for concrete patient [5]. In case untimely justified prosthesis it can happen to its excessive loading or patient responds wrong by bad stereotype of walking. Especially long-term use of such prosthesis can bring series health problems.

From submitted facts the following problem was defined : **Study of mechanical properties of transtibial prosthesis designed for lower limbs (type used after amputation bellow knee) at different loading modes, evaluation of prosthesis function and response of patient on its unfit assembly and setting.**

The globally formulated problem requires multi-disciplinary search solution and comprehensive analysis to many magnitude and factors.

In our work we will only focus on quantifiability of mechanical properties via measurement of longitudinal strain on tube adaptor, from which we will determine mechanical stress of adaptor and outer force effects create these straining. Gained results will used not only for obtaining the ideas about prosthesis parts straining, but also for sequential FEM analyses of selected components.

3.1. Objectives

The aim of this measurement was to verify gauging chain and obtain basic conception about loading and mechanical stress of tube adaptor. Main result of gauging was to determine strain on adaptor in different loading modes. Measurement can be termed like preparative and it is necessary for planned complex experiment. Further experiment will aim at the summary analysis of kinematic magnitudes, resulting forces from mobile force plates and strain on artificial limb. Similar complex analysis was not yet published.

3.2. Methodology and decision procedure

For problem solution an experimental simulation has been selected. Via electric method with strain gauge utilization was investigated strains of selected prosthetic components. Because experiment had preliminary character, following scenario was used during measuring:

1. Checking gauging chain on testing machine ZWICK Z020.
2. Checking measured values compare with analytical solving.
3. Loading of prosthesis in real environment, i.e. measurement on patient with prosthesis

4. Presentation and analysis results

4.1. Gauging chain and strain gauge wiring

Gauging chain (fig. 2) consists of strain gauge system stick on tube adaptor (fig. 1, 4), eight data channel gauging card Spider 8, laptop with Beam Spider software and wiring. Strain gages enable measuring linear strain from tension-compression, bend and torsion loading.

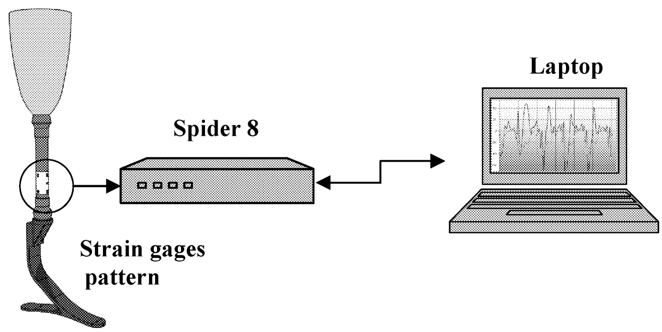

Fig.2: Measuring chain

Strain from bending load was measured by four strain gages deployed around tube per 90 degree (fig. 3, 5). Couples strain gages are connected to the half bridge. It was possible to gage strain from bend in two planes. For the case where torsion is measured strain gages are engaged to the full bridge. There are two dual strain gauges placed on opposite sides of tube in the same height.

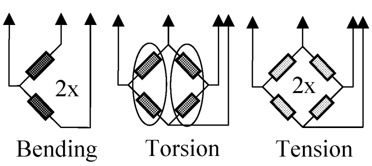

Fig.3: Connection of strain gauges

In the case of tension-compression measuring four double strain gauges are connected. Strain gages are arranged around circumference of tube (per 90 degree). Always two opposite strain gauges are connected to the full bridge.

Signal from strain gauges was carried to the gauging card Spider 8. Sampling rate was adjusted on 300 Hz. Presentation of metering values was realized through laptop and control software Beam Spider.

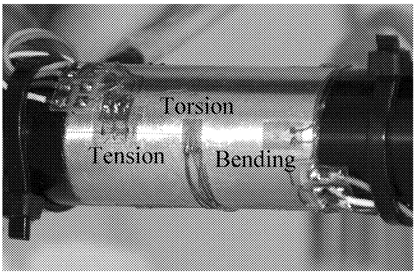

Fig.4: Preview of strain gage placement on prosthesis tube

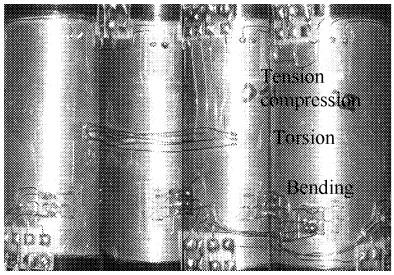

Fig.5: Preview of strain gages placement on adaptor (photo from four sides)

4.2. Measurement on testing machine ZWICK Z020

Measurement on testing machine ZWICK Z020 was effected for basic verification of correct wiring functionality and check measuring technique including software. This appliance is mechanical, computer controlled testing machine for compression and tension testing. Maximum value of load is 20 kN. Machine is equipped by the sensor Multisens for measuring of extension with accuracy of 0.1 micrometers. Tube adaptor of the prosthesis was fastened in upper and lower jaws via steel friction-ball (fig. 7). This way of fastening ensured that the load was equally transferred on adaptor forehead. This point ensures (on distinguishing level) best load by simple pressure and eliminates additional bend and torsion load. On the top end of tube adapter a dural linkage was fixed and on the lower end steel linkage was used. Both linkages reduce creation of bearing stress at the end of tube adaptor.

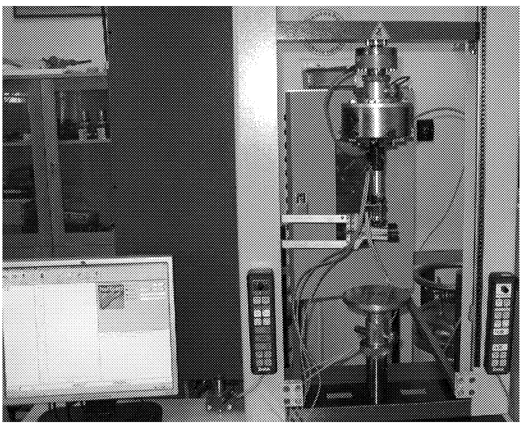

Fig.6: Measurement on ZWICK Z020

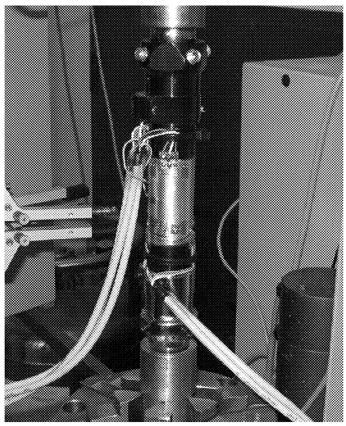

Fig.7: Gripping of tube adaptor

Artificial limb was loaded by axial force 800 N. Data from strain gages was recorded by measuring card Spider. From relevant strain gage was deducted that applied load 800 N corresponds to strain of value $\varepsilon = 61\,\mu\mathrm{m/m}$. Analytical solutions confirmed this valuation with adequate equality.

$$\varepsilon = \frac{F}{E\,S} = \frac{800\,\mathrm{N}}{0.70\times10^5\,\mathrm{MPa}\cdot 184\,\mathrm{mm}^2} = 62.1\,\mu\mathrm{m/m}\ ,$$

where F is axial force, S is cross-sectional area of the tube and E is modulus of elasticity.

Correct function of other strain gage was tested only via manual loading, because check on testing machine would request construction of special fixture for bending and torsion loading.

4.3. Measurement on patient

Measurement was realized in premises of ING corporation, s.r.o. – Ortopedická protetika Frýdek-Místek. Gauging was performed thanks to modular design of the prosthesis. Strain gages were built-in the tube adaptor. Patient was instructed about measuring scenario. Gauging contained standing on artificial limb, standing on the both limbs, direct slow walk, slow downhill walk and downstairs walk. For each load stage, patient walked through predetermined section bounded by length of wiring. Measurement was repeated five times for all stages. Patient's weight was 70 kg.

As shown in fig. 11, at each realization patient walked with different gait speed. That is why each gauging differs from each other. With this also relates changes in strain values, because they depend on gait cycle. Generally, the measured curves of strain range inside specific band. Values published in graphs are already corrected by valid 'bridge factor' adjusted on gauging card.

Gauging 1 – standing position on artificial limb

Primary basic gauging was measuring standing on prosthesis. In the first instance, patient had both limbs side by side. Patient had lightly touched the assistant for keep up balance. Fig. 8 shows, that in this position of lower limbs is patient forced to keep balance via tilting, torsion loading is practically zero, compression loading is almost constant, however bending is dominant (fig. 8).

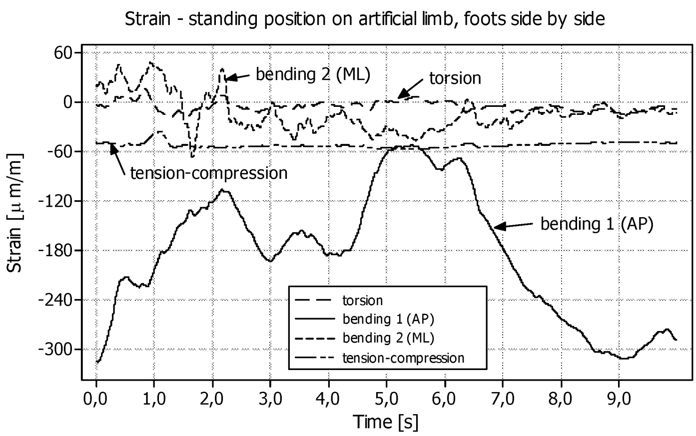

Fig.8: Standing position on prosthesis; AP – anterior posterior (gait direction); ML – medial lateral (perpedicular to gait direction)

Sequentially measurement was performed, whereat patient was standing on artificial limb and had foots in alignment, so healthy leg forward before limb with artificial limb. Position could be compared to situation, when patient stand on line delineated in front-facing walking and healthy leg isn't loaded (fig. 9).

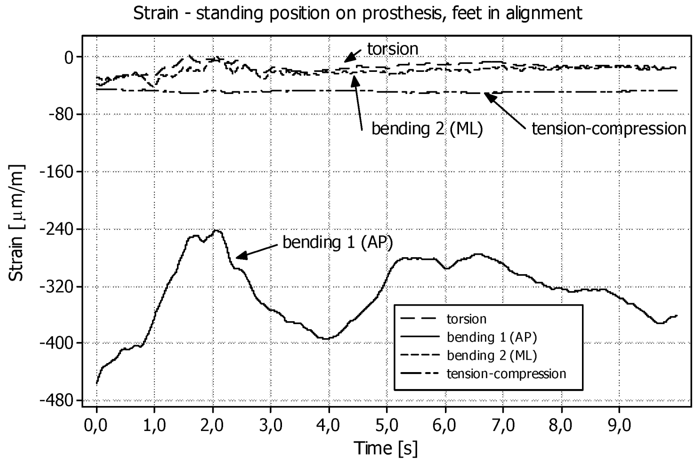

Fig.9: Standing position on prosthesis, feet in alignment

Gauging 2 – straight walk

Patient was standing on both limbs (leg and prosthesis). He initiated gait by artificial limb. After strain values exceed 5 μm/m, measurement has been automatically started. Measurement was realized five times in sequence. Complete measurement record is described in Fig. 11. It is only illustrative record of strain from compression load in adapter axis direction.

Fig.10: Gait analysis

For clear orientation and description in measured data only one measurement was chosen. In Fig. 12 are shown strains from torsion load, tension-compression and bending in walking direction and upright on walking direction. Most significant is strain from bending load in direction gait. Maximum bending stress is reaching (after re-count) values about 60 MPa.

Zero strain values from tension-compression loading characterize a state, when patient transfered loading on healthy limb and prosthesis was unloaded.

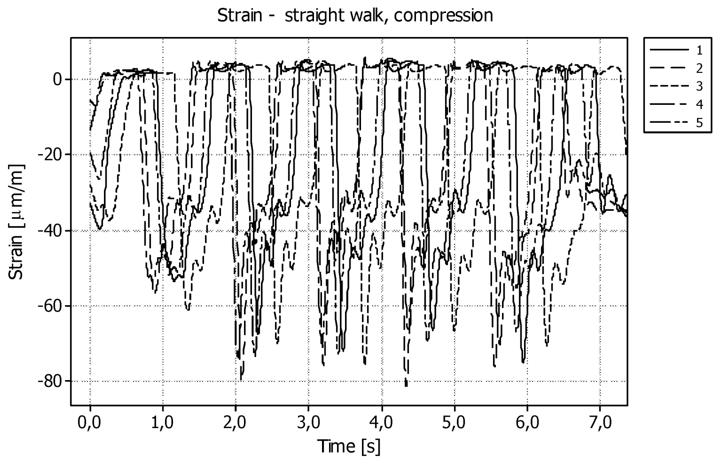

Fig.11: Strain (five measurement)

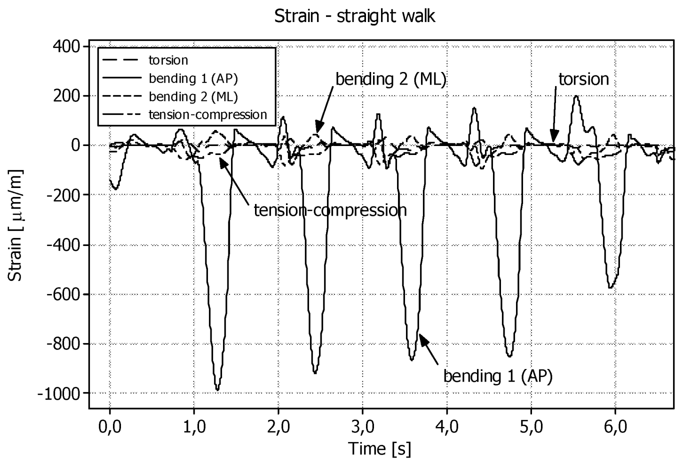

Fig.12: Strain – straight gait

Gauging 3 – downhill walk

Alike in previous case, five gauging of gait (downhill walk) has been performed. Figure 13 shows only one chosen curve of strain.

Gauging 4 – downstairs walk

The measurement was realized repeatedly five times in sequence. Testing track was created from five staircases. Individual steps are marked in fig. 14. Odd numbers represent state, when patient carried loading to healthy limb. Even numbers represent state, when inmate carried loading to prosthesis. From the graph is evident that strain caused by the bending load is only in tension side of the tube adaptor.

5. Conclusion

In this work results of introductory experiment were presented. Primary aim of the experiment was to verify gauging chain for strain measuring on prosthetic tube adaptor.

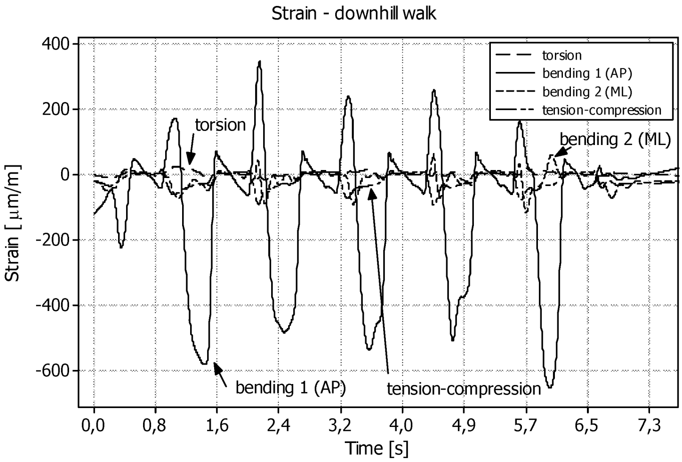

Fig.13: Strain – downhill walk

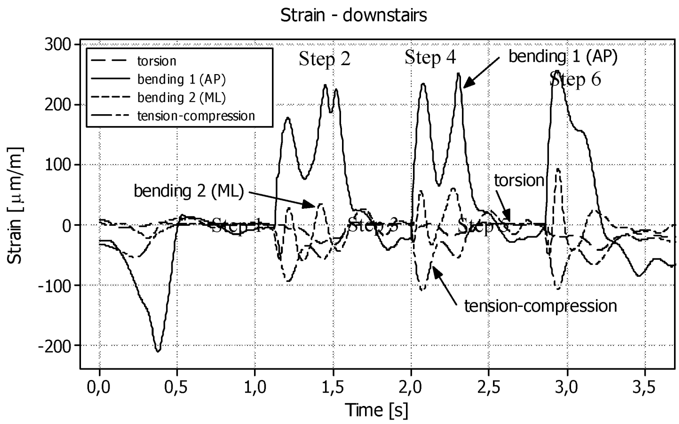

Fig.14: Strain – downstairs

The next objectives:
- detect and repair possible failings,
- evaluate readiness of experimental team for more complex measurement,
- consider possibilities of patient cooperation.

Testing procedure was performed in different modes of loading, in order to gain ideas about loading characteristics of prosthesis adaptor. Analysis of measured results verified correct function of the strain gauge wiring. Team gained valuable experience about the measurement heftiness with patient, about technical problems that were discovered during gauging and following data processing.

For the complex analysis of prosthesis and its time response on loading, it is necessary to know kinematic magnitudes describing the position, speed and acceleration of designated points on lower limbs and patient body and size and direction of reaction forces between base and patient.

On this account a new experiment is scheduled, in which together with measurement of strain (strain gauges), measurement on mobile force plates and measurement of kinematic magnitudes via motion capture system will be presented. Force plates will provide information about sizes and directions of reaction forces (between patient and plates). Motion capture system will record three-dimensional information of position and angles in chosen single joints. Measurements will start together in the same moment. Then will be possible to determine reaction forces and strain from base in given time moment, and consider patients reaction to prosthesis.

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