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SIMULATION OF KNEE JOINT DYNAMICS AND KINEMATICS UNDER REALISTIC CONDITIONS

REALISTICKÉ DYNAMICKÉ A KINEMATICKÉ PODMÍNKY SIMULACE V KOLENNÍM KLOUBU

Abstract

In vitro simulations can be an important instrument to predict the behaviour of new prosthesis designs and materials during the time of wear. In technical practice it is impossible to achieve the same dynamic conditions as during *in vivo* of joints after implantation. Kinematics and dynamics of applying load on the components must simulate the real patient's movements. Simulation under conditions not identical with that *in-vivo* may result in false information. Important parameters are variable loading, ranges of sliding and rolling movement, experimental temperature and volume of lubricant.

Abstrakt

Významným instrumentem předpovídajícím otěrové chování nových konstrukcí endoprotéz a materiálových dvojic může být simulace „in vitro". V technické praxi není možné dosáhnout shodných dynamických podmínek „in vivo", které jsou v kloubu po implantaci. Kinematika a dynamika zatěžovací síly musí simulovat skutečné pohyby pacientů. Simulace při podmínkách rozdílných od podmínek „in vivo" může přinášet chybné informace o otěrovém chování. Významnými parametry z pohledu realistické simulace je proměnlivé zatížení, rozsah pohybu smýkání a odvalování, experimentální teplota a množství lubrikantu.

1 INTRODUCTION

A major motivation of this research project is to increase the life of present prosthesis designs. This is necessary, because actually the perspectives for young patients are not good. The surgical standard for primary implantation is the Total Knee Arthroplasty with a maximum of one or two revision operations. The effect of damaged joint components on patients is widely described in medical literature. Generally, cases of damage are fatigue fracture of metallic parts and adhesive wear of Ultra High Weight Polyethylene components [1]. Pre-clinical testing of joint components is necessary for determination of the probability of damage. In technical practice it is impossible to achieve the same dynamic conditions as during in vivo of joints after implantation. Proper "in vitro" testing of parts individually and also of all components can be achieved only with simplification of load conditions. This simplification must not reduce the predicative ability of "in vitro" experiments.

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2. MATERIALS AND METHODS

2.1. Simulator

The KKK ELO 2007 simulator has been designed to reproduce the situation of the implanted prosthesis as precisely as possible and in comparison to earlier simulators – represents an improvement in the approximation to in-vivo conditions. Emphasis has been put on variable loads, adding of sliding and rotational motion to the flexion and controlling temperature, velocity and volume of the lubricant.

The simulator of knee joint replacement was designed to simulate flexion, AP motion (Anterior – Posterior) and IE rotation (Internal – External). The range of motions is limited only by the physiological conditions of movement and specimen geometry. The components rotate each others around medial condyle. It is possible to set the distance ε on required value, but it is not possible to change it during the time of an experiment. The driving system of the moving unit makes setting of position and force loading in the time moment possible. Active motion is not possible in the Lateral-Medial direction and Distal-Proximal. The same is valid to the Abduction-Adduction motion.

2.2 Simulated motions and loading

The simulated motion is defined by flexion angle [°], IE rotations [°] and AP displacement [mm]. The motion is described by periodic harmonic function (1); enable setting of proper position in required time. The optimal description of substitute function has form:

$$\alpha^{flexion}(t) = \overline{X}_i + \sum_{n=1}^{6} \left(A_i * \sin(* \pi * \varphi_i * t_c + B_i)\right), \qquad (1)$$

where:

$\overline{X}_i$ - mean value of flexion angle [ ],

φ_I -frequency [/s],

A_i - amplitude [ ],

B_i - phase shift [ ],

t_c - time from the whole cycle [ ].

Analogously description of harmonic function for $\beta^{IE}(t)$ (IE rotation) with index *j*, and also for $\alpha^{AP}(t)$ (AP displacement) with index *k* and for $F^{load}(t)$ (load) with index *l* are obtained. Coefficients *A*, *B* and φ with indexes *i*, *j*, *k* and *l* can be obtained from experimental data by approximation using the least square method. Quality of approximation is described by coefficient of regression (2):

$$R^2 = 1 - \sum_{n=1}^{N} (y_n - y(x_n))^2 \Big/ \sum_{n=1}^{N} \left(y_n - \overline{y}\right)^2, \qquad (2)$$

where:

y_n - n–th experimental measured value [ ],

$y(x_n)$ - value calculated by regression [ ],

$\overline{y}$ - mean value [ ].

Analogously we obtain description for function with indexes *j*, *k* and *l*.

2.3 Loading cycle

The simulated motion is described by loading cycle Fig. 1. In any time instant it is defined by the form harmonic function flexion angle, IE rotation, AP motion and F^{Load} axial loading force. The motion can be described by coefficients *X*, *A*, *B* and *φ* with indexes *i*, *j*, *k* and *l* obtained from calculation by the least square method. For given motion has been applied experimental data from issues of authors [2-5]. Results are shown in Tab. 1. For any from 6 realized daily activities is needed to find 76 characteristic constants. Either of constants can be 0. While using of constants from Table 1 takes coefficient of regression the value with respect to mean value of all authors for flexion $R^2_{flection}$ = 0,995 , IE station R^2_{IE} = 0,998, AP motion R^2_{AP} = 0,971 and axial loading force R^2_{load} = 0,958.

3. DISCUSSION

Most of the test facilities available on the market simulate constant slow walk but neglect everyday activities like standing, running or stair climbing. According to [6] constant walking represents just one of the patient's everyday activities. According to the results it is clear, that walk is just 10% of the human daily locomotive activity. Dependence on loading during various movements was studied. Movements during which joint components are maximally loaded can be specified from the experimental results. Among the most unfavourable activities are jogging, stair climbing, downhill and normal walking etc. Many authors have already measured the influence of force exerted on knee joint components. The variability of results is caused a relatively low number of patients, different conditions during experiments and also by various measuring processes and interpretations of results of loading experiment. By comparing with results obtained by other authors we can see the same basic trends and characteristics of loading curves.

Simulation, which allow motions and loading just in the direction of flexion, IE rotation and AP displacement, is quiet considerably simplified in comparison to realistic kinematics and dynamic of the knee joint. The real knee joint has six degrees of freedom. For tribological tests are really important dynamic of loading and range of motions and their rapidness. By studying of damaging surface of the knee-components in-vitro is supposed that damaging mechanism, which has been detected by experiments, is the same as damaging mechanism of joint-components in the patient's joint after implantation. There are many aspects which have to be fulfilled to substitute realistic conditions. Realization of loading process by harmonic functions means fundamental simplification in definition of motion and it setting into device, also the local effect on loading and motion curve is minimized. It is impossible to clearly state the influence of using harmonic functions on tribological processes. The main reason to describe the process by harmonic functions is great difference between experimental results from various authors by describing the local effects. The difference data results are caused by physiological difference motion of individual subjects and experiment conditions.

4. CONCLUSIONS

On base of experimental results the loading cycle was determined. Because of many different experimental and known data it will be necessary to clarify characteristics defined harmonic functions. Approximations by using harmonic function show a possible way, how to describe motions and loading modes on simulation device. Surprisingly by comparing experimental results with present standard ISO 14 243 a lot of differences had been observed. According to future published experimental results will be possible to better specify harmonic functions to define tribological conditions. In future it will be necessary to clarify dependence of loading force on velocity of walking and other motions.

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Tab. 1 Coefficients of harmonic function - normal gait

		index - i, j, k, l					
		1	2	3	4	5	6
A_i^f	flexion	5,21	-21,16	15,04	-3,37	-0,27	-0,04
B_i^f		0,02	6,40	-1,26	15,31	14,48	13,16
φ_i^f		0	1,00	2,00	2,99	5,02	7,48
X_i^f		22,38					
A_j^r	IE rotation	3,83	1,28	0,20	-0,17	-	-
B_j^r		1,33	-1,22	-1,14	5,15	-	-
φ_j^r		1,00	2,00	3,00	3,99	-	-
X_j^r		-2,61					
A_k^d	AP displacement	1	-0,75	-0,57	0,5	0,25	-
B_k^d		1,13	-1,16	0,02	-1,42	-0,25	-
φ_k^d		1,00	2,00	3,00	4,00	5,00	-
X_k^d		-1,39					
A_l^L	axial force	0,95	0,42	-0,35	0,09	-0,1	0,04
B_l^L		-0,75	0,65	1	0,9	-1,25	-0,3
φ_l^L		1,00	2,00	3,00	4,00	5,00	6,00
X_l^L		1,26					

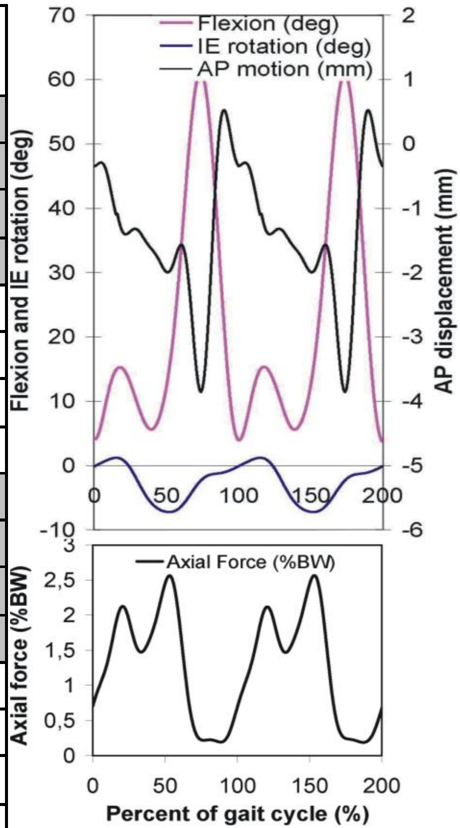

Fig. 1 Loading cycle (normal gait 4 mph)

REFERENCES

[1] COSTA, L. ET AL. *UHMWPE for Arthroplasty*. Torino, 2000, ISBN 88-7711-347-2.

[2] MARIN, F., ET AL. On the estimation of knee joint kinematics. Elsevier: *Human Movement Science*, 1999, Vol. 182, pp. 613-626.

[3] GODEST, A.C., ET AL. Simulation of a knee joint replacement during a gait cycle using explicit finite element analysis. Elsevier: *Journal of Biomechanics*, 2002, Vol. 35, pp.267-275.

[4] LAZ, ET AL. Effects of knee Simulator Loading and Alignment Variability on Predicted Implant Mechanics: A Probabilistic Study. Wiley InterScience: *Journal of Orthopeadic Research*, December 2006, Vol. 24, pp. 2212-2221.

[5] HURWITZ, D.E., ET AL. Dynamic knee loads during gait predict proximal tibia bone distribution, Elsevier: Journal of Biomechanics, 1998, Vol. 31, pp. 423-430.

[6] MORLOCK, ET AL. Duration and frequency of every day activities in total hip patients. Elsevier: *Journal of Biomechanics*, 2001, Vol. 34, pp. 873-881.

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