Nonlinear dynamic behavior of the human knee joint Part II: Time-domain analyses : effects of structural damage in postmortem experiments
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A description is given of the results obtained for step excitation for two human knee joint specimens using a time-domain analysis technique. As was expected from the results of a previous study, the magnitude of the dynamic load applied has a marked influence upon the stiffness and damping values for the two observed vibration modes. Deliberate damaging of selected joint elements also yields a well observable change in the dynamic behavior of the joint although these changes are difficult to interpret. Here the use of a nonlinear dynamic numerical model of the knee joint seems indispensable. An important observation is, however, that the experimental method discussed here enables to quantify the behavior of the joint and therefore may provide a valuable tool for validation of such a model.

1 Introduction

From the results of postmortem experiments on human knee joint specimen under random excitation (Jans et al., 1988, Dortmans et al., 1991), it was concluded that a description of the knee joint in terms of a linear system is acceptable, if the system parameters are considered to depend on the magnitude of the applied dynamic load. To investigate this dependence a simple excitation technique may be applied such that the relevant system parameters may be extracted from measured time-domain signals. The decision to apply step excitation for this purpose is motivated as follows:

*Due to the nonlinearity of the behavior of the joint, the results obtained from a dynamic analysis are likely to depend on the frequency contents of the excitation signal and on the initial conditions (displacements and velocities at the start of the experiment). The latter can (fairly) well be controlled for step excitation.

Step excitation yields an excitation signal in which all relevant frequency components are excited, such that the expected resonance phenomena become observable (in contrast to sinusoidal excitation in which only one particular frequency component is excited.)

To analyze the behavior of the joint under step excitation, experiments can be carried out which are similar to those described in earlier papers (Jans et al., 1988 and Dortmans et al., 1991). Compared to those experiments both the experimental set-up and the preparation of the joint specimen are identical, merely the type of the excitation signal has been changed, as will be discussed in section 2.

2 Experimental Methods

Suppose a force $f_\text{eo}$, which has the pattern given in Fig. 1, is applied along one of the coordinate axes of a vector base connected to the tibia, such that an initially applied constant force $f_\text{eo}$ is removed at $t = 0$. This particular form of step excitation can be applied by means of the installation shown in Fig. 2. A force transducer (a) is connected to the brass housing R. This force transducer is connected to a small-sized electromagnet (b), which on its turn is connected to a loading weight (c) by means of a flexible rope (c) (length approximately 0.5 m). This rope is led over a pulley (d) which is flexibly suspended in the hook (f) of a remote control travelling crane. With this installation the step excitation shown in Fig. 1 can be realized as follows:

*The electromagnet (b) is activated and a loading weight is attached to the rope (c).

*Next, the orientation of the rope (c) is adjusted, by movements of the travelling crane, to meet the desired orientation which is inspected visually.

Fig. 1  Pattern of the force exerted on the tibia for step excitation
3.1 Description of the Experiments. Experiments were carried out on 3 knee joint specimens, KNEE6, KNEE7, and KNEE8. KNEE6 was used in preliminary, explorative, experiments to test the experimental procedure described and to find out whether the in-situ operations described in section 3.2 could be carried out. Therefore no reference to the results of the experiments on KNEE6 is made here. The experiments discussed here were done with three prime objectives:

- determination of the behavior of the joint for various values of the force $f_{eo}$ in terms of stiffness and damping values;
- determination of the effect of deliberate damaging of selected joint elements;
- to get an indication about the reproducibility of the results.

As a consequence, the static equilibrium position and the forces on the muscle tendons were not varied in these experiments.

In particular, after change of the static equilibrium position and/or the load on the muscle tendons, reconstruction of a previously used configuration must be done accurately if the effect of damaging of joint elements must be determined for various equilibrium positions and/or loads on the muscle tendons. Previous experiments (Jans et al., 1988 and Dortmans et al., 1991) revealed that such a reconstruction cannot be easily performed due to the nonlinear behavior of the joint. A noticeable effect of the nonlinearities is a kind of locking phenomenon. This means that the sequence in which the loads on the muscle tendons are in- or decreased, strongly determines the kinematical behavior of the joint. In some cases no observable joint movements could be achieved when increasing the load on a particular muscle tendon. The optimal adjustment being unknown in advance, such time-consuming experiments were omitted, moreover as the total time available for experiments on one particular specimen was limited to two days because of autolysis.

The static equilibrium position selected for this purpose is characterized by a flexion angle of 6 of 20 deg (Jans et al., 1988), with $F_a = 120$ N, $F_c = 150$ N, and $F_b = 110$ N ($F_a$ is the force on the pes anserinus, $F_c$ the force on the rectus femoris muscle and $F_b$ the force on the biceps femoris muscle, see Dortmans et al., 1991). This configuration was chosen because at approximately this flexion angle for level walking the highest muscular moments and vertical ground reaction forces have been recorded (Antonsson et al., 1985).

3.2 Operations on the Knee Joint Specimen. The experiments were done on knee joint specimens prepared as discussed in an earlier paper (Jans et al., 1988). In the experiments, a number of measurements were done for different values of the force $f_{eo}$ to obtain an impression about the behavior of the undamaged joint. Next, these measurements were repeated after damaging the joint. For this purpose it was decided to try and determine for KNEE7 the influence of cutting the medial meniscus and the anterior cruciate ligament, whereas for KNEE8 additionally the lateral meniscus was cut. These operations were done in situ without removing the joint specimen from the experimental set-up.

To be able to reach the anatomical structures mentioned above, an incision had to be made along the patellar ligament. After the knee joint specimen had been mounted in the experimental set-up, areas of the capsular fibres could be determined by palpation at both sides of the patellar ligament which could be considered unloaded (in comparison with the patellar ligament itself). It therefore seemed reasonable to assume that in these areas incisions could be made without disturbing the force transmission through the knee joint. The length of these incisions was approximately 40 mm. After these incisions had been made, a window was dissected carefully in the joint capsule on either side of the patellar ligament (see Fig. 3). These windows have a width of approximately 30 mm. Through these openings the infrapatellar pad of fat was removed to obtain an empty volume between the patellar ligament and the tibia and the femur which was necessary to get a view on the anterior cruciate ligament. Measurements carried out before and after creation of the windows and removal of the infrapatellar pad of fat neither showed significant changes in the recorded behavior of the joint.

Next, the anterior horn to the medial meniscus was cut first, by means of a radial incision (a) as is indicated schematically in Fig. 4. After this operation, the anterior cruciate ligament was cut (Fig. 4 (c)) which is a more difficult operation due to the limited view on this ligament in the chosen joint configuration (20 deg flexion). Finally (KNEE8) also the lateral meniscus was cut in a way similar to the medial meniscus (Fig. 4 (b)). To assure that the damage intended to be brought about was actually realized, after the experiments the specimens were inspected visually confirming the effectiveness of the operations described above. After the operations had been carried out no change in the static load on the muscle tendons or the static equilibrium position could be measured.

3.3 Data Analysis. The response of the joint to the step excitation was measured in terms of the accelerations of the
4.1 Pre and Postoperative Results for Step Excitation. The results for the modal parameters $\omega_0$ and $\xi$ for KNEE7 and KNEE8, obtained by step excitation in $y$-direction are given in Figs. 8, 9, 10, and 11.

Figure 8 gives the undamped angular frequency $\omega_0$ for KNEE7 and KNEE8 for experiments in which the force $f_0$ was applied in $y$-direction. As can be seen $\omega_0$ decreases with increasing force values, being a clear indication for the nonlinear behavior of the joint. After cutting the medial meniscus the reasonance frequency increases. This points to an increase of the stiffness
of these operations.

A clear decrease of the stiffness of the joint resulting from each operation is found as for KNEE7, except that the values for KNEE8, medial meniscus cut; KNEE8, anterior cruciate ligament cut; KNEE8, lateral meniscus cut

Fig. 9 The undamped angular frequency $\omega_0$, for vibration mode I for a force $f_\infty$ applied in $y$-direction.
- KNEE7, intact;
- KNEE8, medial meniscus cut;
- KNEE8, anterior cruciate ligament cut;
- KNEE8, lateral meniscus cut

(for this vibration mode) after cutting the medial meniscus. After subsequently cutting the anterior cruciate ligament $\omega_0$ decreases, being an indication for a decrease of the stiffness of the joint, although the stiffness of the joint is still larger than for the intact joint. Figure 8 also shows that the effect of damaging of joint elements is not identical for the various magnitudes of the force $f_\infty$ applied. Cutting the medial meniscus yields the most pronounced changes for a force of approximately 10 N, whereas subsequently cutting the anterior cruciate ligament mainly influences the results for a force $f_\infty$ of 20 N.

As can be seen from Fig. 8 repetition of a particular experiment yields almost identical results. Variation in $\omega_0$ for a repeated experiment are far smaller than those due to a change in the applied force $f_\infty$ or due to damaging of the joint. This indicates that the experimental procedure used to apply the step excitation can be carried out with sufficient reproducibility.

Similar experiments were carried out for KNEE8 yielding the results for $\omega_0$ given in Fig. 9. For the intact joint a similar behavior is found as for KNEE7, except that the values for $\omega_0$ are at a higher level. In contrast with the results of the experiments carried out on KNEE7, successive cutting of the medial meniscus, the anterior cruciate ligament and the lateral meniscus always yields a marked reduction of $\omega_0$, indicating a clear decrease of the stiffness of the joint resulting from each of these operations.

The values for the dimensionless damping $\xi_1$ corresponding

Fig. 9 The undamped angular frequency $\omega_0$, for vibration mode I for a force $f_\infty$ applied in $y$-direction.
- KNEE7, intact;
- KNEE8, medial meniscus cut;
- KNEE8, anterior cruciate ligament cut;
- KNEE8, lateral meniscus cut

Fig. 10 The dimensionless damping $\xi_1$, for vibration mode I for a force applied in $y$-direction.
- KNEE7, intact;
- KNEE7, medial meniscus cut;
- KNEE7, anterior cruciate ligament cut

to the values for $\omega_0$ given above are presented in Figs. 10 and 11, for KNEE7 and KNEE8, respectively.

- For KNEE7, $\xi_1$ for the intact joint decreases with increasing value of $f_\infty$ although these changes are only modest compared to those found for KNEE8. Cutting the medial meniscus results in a decrease of the damping $\xi_1$ (except for the highest applied force $f_\infty$). Subsequently cutting the anterior cruciate ligament does not significantly influence the damping values, except for the highest applied force $f_\infty$.

4.2 Reproducibility of the Results. From Figs. 8 through 11 it is observed that repetition of a particular experiment does

Fig. 10 The dimensionless damping $\xi_1$, for vibration mode I for a force applied in $y$-direction.
- KNEE8, intact;
- KNEE8, medial meniscus cut;
- KNEE8, anterior cruciate ligament cut;
- KNEE8, lateral meniscus cut

Fig. 11 The undamped angular frequency $\omega_0$, for vibration mode I for a force applied in $y$-direction.
- KNEE8, intact;
- KNEE8, medial meniscus cut;
- KNEE8, anterior cruciate ligament cut;
- KNEE8, lateral meniscus cut

Fig. 12 The undamped angular velocity $\omega_0$, and the dimensionless damping $\xi_1$, for vibration mode I for a force applied in $y$-direction.
- KNEE8 day 1;
- KNEE8 day 2
not yield significant differences in the results. As the repeated experiments were carried out within a few minutes time, the "short-term" reproducibility is considered to be good. As mentioned in a previous paper (Jans et al., 1988), for the experiments with random excitation removal of the knee joint specimen from the experimental set-up, storage overnight and remounting of the specimen the day after did not yield significant changes in the results obtained. This "long-term" reproducibility was not analyzed in detail, however. For the experiments with step excitation on KNEE8 this was focused on in more detail. Before presenting the results for such repeated experiments on day 1 and day 2 it is noticed that this procedure may be influenced by:

* Differences in the static equilibrium position of the specimen (which were kept as small as possible by proper measurement of the position of a number of fixed points on the tibia relative to the foundation of the experimental set-up: accuracy 0.5 mm.);
* Differences in the load exerted on the muscle tendons (which were kept within 5 N);
* Differences in the behavior of the joint due to progress of autolysis.

Therefore it is felt that the results for the parameters urad and € shown in Fig. 12 show a good reproducibility, although both the resonance angular frequency and the damping attain a somewhat higher value on day 2.

5 Discussion of the Results

The results from a time-domain analysis for two knee joint specimens have been presented in terms of the modal parameters describing the best-fitting linear system. From the data given the following conclusions can be drawn:

* The dependence of the stiffness and damping characteristics of the joint on the magnitude of the applied force must be taken into account as this influence cannot be neglected compared to the influence of damaging of the joint.
* For the intact joint, the resonance frequencies decrease with increasing force $f_{\text{ex}}$. This is in agreement with the results obtained for random excitation (Dortmans et al., 1991) where an increase of the variance $\sigma$ of the excitation signal yielded the same characteristics. For the damping values no consistent pattern was found.
* The influence of damaging of joint elements upon the stiffness and damping characteristics can well be determined. Although the changes found are well bounded, they are significant as they are far larger than the variances in the results obtained for repeated experiments. This also indicates that step excitation is a useful tool to analyze the behavior of the joint.

The results obtained for KNEE7 and KNEE8 show a rather distinct behavior for vibration mode I after cutting the medial meniscus and the anterior cruciate ligament. It might have been expected on forehand, that the joint elements contribute to the stiffness of the joint and loss of their function does not influence the behavior of the remainder of the joint elements. Obviously for KNEE7 this assumption does not hold. Further research is necessary to establish whether these phenomena are typical or whether this is the result of uncontrolled changes in the parameters describing the static equilibrium position of the joint. Especially this applies for the static equilibrium position of the joint which could only be measured with limited accuracy. A numerical model of the knee joint is indispensable for such an analysis as this provides a tool for systematic analysis of the influence of various measurement parameters.

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