Force measurements in a Distal Femoral Replacement *in vivo* by telemetry

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A custom-made distal femoral replacement was instrumented to measure axial force, torque and bending moments in the prosthesis shaft. Data are reported for the following activities at 1 year post-op: walking, stair climbing and descending, jogging and jumping. Mean peak shaft axial forces were as follows: 3.1BW for jogging, 2.7BW for stair descending, 2.2BW for walking, 2.1BW for stair ascending. Bending moments about the AP and ML axes for these activities were in the range 6.3-8.3BWcm and 3.5-5.5BWcm respectively. Axial torques were between 0.9-1.4 BWcm, inwardly directed.
Keywords: force, telemetry, femoral, knee forces, *in vivo*

INTRODUCTION

The forces at the hip joint have been determined indirectly (1,2) and directly using telemetry (3,4), and directly in a proximal femoral replacement (5). For the knee joint, forces have so far only been obtained using indirect methods (6-9). While calculated results can be applied to any number of subjects, certain necessary assumptions lead to uncertainty in the data. Telemetry data produce direct measurements of the forces in implants, although only a limited number of subjects can be studied. Extrapolating results to the intact joint depends upon the extent to which the joint mechanics and surrounding musculature has been altered. In a recent study (10), the forces at the knee itself were estimated based on the data from an instrumented prosthesis and kinematics.

An instrumented distal femoral replacement measured axial force, moments in the frontal plane (varus-valgus), in the sagittal plane (flexion-extension), and about the long axis of the prosthesis (axial torque). Strain gauges were bonded to the internal walls of a cavity in the prosthesis, and wired to electronics housed inside it. Power was induced and data telemetered electromagnetically using one implanted and one external coil.

METHODS AND MATERIALS

The instrumented prosthesis is described elsewhere (10). The mechanical structure is shown in figure 1. The prosthesis was made as two main sections, both from solid Ti-6Al-4V bar: an instrumented proximal part, including the IM stem, and a distal part, spigotted onto the knee joint. The length was customised for each subject and the assembly calibrated for force and moments. A rotating hinge knee joint allowed some rotational laxity about the longitudinal axis. The prosthesis had 5 strain channels, each sampled at 100Hz. The strain gauges were wired to amplifiers, whose outputs were multiplexed and used to pulse-interval modulate a serial signal. Power was induced in the implant by inductive coupling between an implanted coil and one applied around the leg during the measurements. The serial signal containing strain data was telemetered over the same inductive link in real time, and thence to a remote portable PC by a radio link. A calibration matrix was used to convert the signals to forces and moments, which were displayed in real time and saved. Since the energiser was battery powered, the subject was unencumbered by any trailing cables, allowing full freedom of movement.

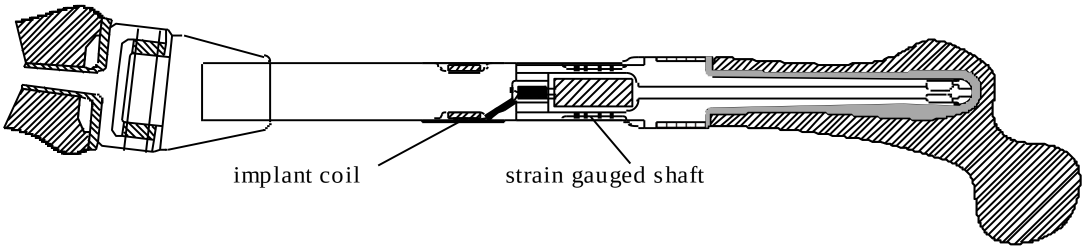

Figure 1 Instrumented distal femoral replacement and fixation (anterior view)

The prosthesis was implanted into a 41 year old female (GF). She had a malignant fibrous histiocytoma of the right distal femur, requiring resection of the distal 277mm of the femur, together with vastus intermedius and part of vastus lateralis, figure 1. At intervals after surgery the external telemetric apparatus was applied and the subject undertook several everyday activities. These included: level walking and jogging, ascending and descending stairs, and single and continuous vertical jumping. The walking speed was measured optically. When negotiating stairs (18 steps at a slope of 31°), the subject walked normally, i.e. each foot traversing two steps, with minimal handrail support. During single jumps the subject flexed her knees slightly, took off, and landed back to the bilateral standing position. During repeat jumping there was no pause between landing from the last jump and taking off on the next. The subject wore casual trousers and 'trainers'. Data were logged for 10-20 seconds, depending on the activity.

RESULTS

Data are reported here for a single session held at 1 year post-op. Forces and moments are given in bodyweight (BW and BWcm). Data for level walking at 1.1m/s are shown over 3 gait cycles in figure 2. There were 3 axial force peaks: the first at just over 1 BW occurred just after heelstrike, and the other two (main peaks) occurred during mid and late stance. A varus moment acted during stance, the peaks of which were slightly in advance of the main axial force peaks. A sagittal plane moment, acting in a direction consistent with quadriceps activity (hip flexion), peaked after heelstrike and then reduced to zero by toe-off. The axial torque, acting to rotate the tibia inwards, peaked at 1BWcm. Averaged peak force and moment values for each activity are given in Table 1.

Average axial shaft forces during one gait cycle for each of the activities are shown in figure 3. For each activity, several (n=5 to 12) consecutive gait cycles were numerically compressed to the same arbitrary length and averaged. Gait cycles were separated at the minimum value between successive cycles. Averaged peaks were between 2.0 and 3.1 BW, jogging and walking downstairs giving the highest values. Jogging produced a similar pattern to walking at heelstrike but generally had only one main peak, which was the highest recorded during any activity. In stair climbing there was a small initial peak followed by two main peaks of similar magnitude. In stair descending there was a large peak around heelstrike followed by two main peaks. In single jumping there were two main peaks corresponding to take off and landing. In continuous jumping the landing and take off phases were also discernible as separate peaks.

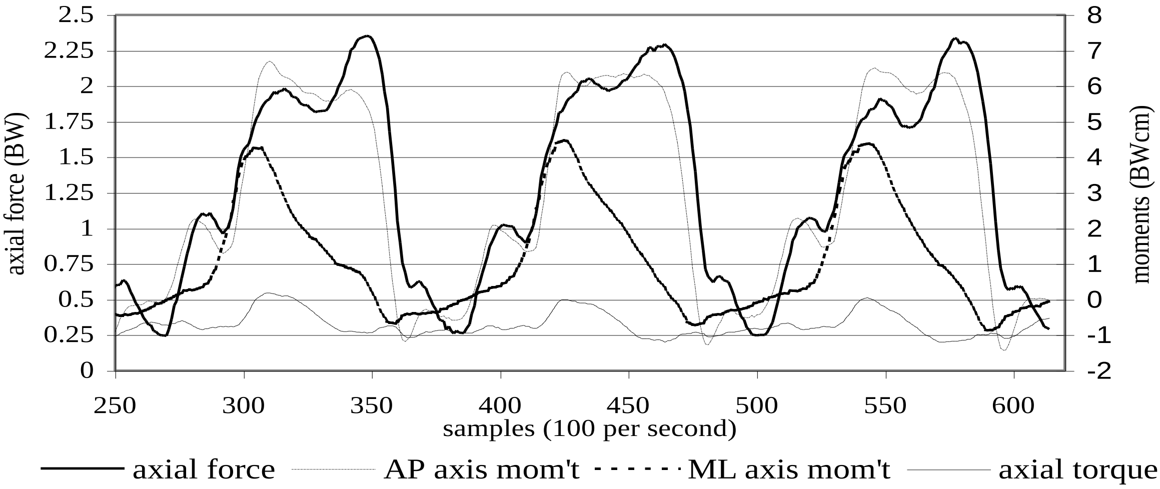

Figure 2 Force and moments over 3 gait cycles during level walking at 1.1m/s

Activity	Axial force BW (kN)	Moment about AP axis BWcm (Nm)	Moment about ML axis BWcm (Nm)	Axial torque BWcm (Nm)
Walking	2.17 (1.47)	6.65 (45.0)	4.35 (29.4)	1.09 (7.4)
Jogging	3.08 (2.08)	8.31 (56.2)	5.54 (37.5)	1.38 (9.3)
Stairs up	2.14 (1.45)	6.32 (42.8)	5.35 (36.2)	0.90 (6.1)
Stairs down	2.68 (1.81)	7.10 (48.1)	3.47 (23.5)	1.07 (7.2)
Single jumps	2.35 (1.59)	3.76 (25.5)	4.33 (29.3)	1.12 (7.6)
Repeat jumps	2.44 (1.65)	3.40 (23.0)	4.45 (30.1)	1.05 (7.1)

Table 1 Mean values of peak axial force and moments for each activity (n = 4 to 9)

DISCUSSION

A normal gait pattern in walking was recorded by motion analysis for this subject (10). This suggested that the muscle actions were reasonably well compensated despite loss of part of the quadriceps, and that the measured forces might be close to those for the natural anatomy. Not unexpectedly, the highest axial forces recorded were for jogging, with walking downstairs giving the next highest values, the latter being consistent with the work of Morrison (6). The initial force peak in walking at heelstrike was much lower than that predicted by Morrison (7) however, although it could still be due to the hamstrings decelerating the extending knee. The first main force peak (in mid stance) is consistent with the quadriceps acting against the high knee flexing moment. Data from e.m.g. has identified gastrocnemius activity at the second force peak just before toe-off (7). In our subject, these muscles would at best be attached to a soft tissue sleeve around the implant, but possibly the patient applied the hamstrings also, to stabilise the knee.

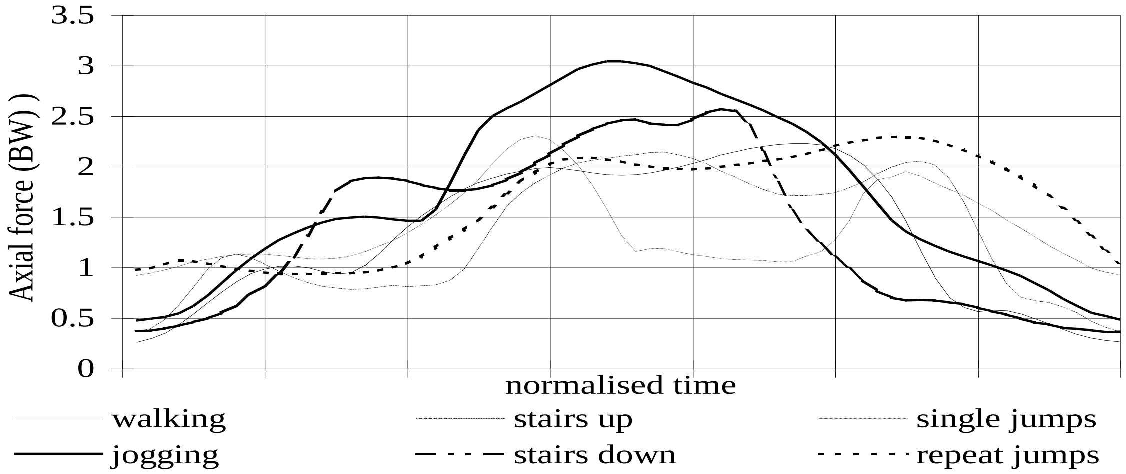

Figure3 Mean axial force (n=5 to 12) for different activities during one gait cycle

There was a high varus moment at the strain gauge level in all gait activities. There was evidently no asymmetrical muscle activity to reduce the moments, although the axle of the rotating knee hinge would automatically provide varus stability at the knee, and in the normal knee the varus moment steadily reduces down the femur to give low values at the knee (11). There was a moderately high axial torque acting, in the overall range 0.9-1.6 BWcm (6.1-10.8 Nm). This is similar to that calculated for normal subjects (7). If this torque was generated at the foot, it could be transmitted through the rotating knee hinge because the surfaces were partially conforming allowing torque to be transmitted with axial rotation, in the presence of an axial force.

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