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Short Communication

In Vivo Measurements Show Tensile Axial Strain in the Proximal Lateral Aspect of the Human Femur

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Summary: Two conflicting theories exist concerning the stress pattern for the proximal lateral aspect of the human femur. According to the classic theory of Pauwels, a bending moment on the femur leads to compression medially and to tension laterally. The alternative theory is that muscle forces contribute to a moment-free loading of the femur, with both the medial and lateral cortices subjected to compression. To examine these theories, we measured the strain at the external surface of the proximal lateral aspect of the femur of two female patients undergoing surgery for "snapping hip syndrome." During the surgical procedure, a strain-gauge rosette was bonded to the lateral aspect of the femur and the cortical strains were monitored while the patient performed a series of activities. In both patients, principle tensile strain increased significantly during one-legged stance, walking, and stair climbing as compared with that during two-legged stance. During each loading situation, the principal tensile strain was aligned within 22° to the longitudinal femoral axis. Dynamic strain measurements consistently revealed tensile axial strain at the lateral aspect of the femur during each activity. The present study supports the classic bending theory of Pauwels and demonstrates that the proximal lateral aspect of the femur is subjected to tension during the stance phase of gait.

According to traditional theory on biomechanics of the hip, a bending moment acts on the proximal aspect of the femur during single-legged stance and during the stance phase of gait (9,16-19). This bending theory is based on static analysis, elastic-coating studies, and *in vitro* strain measurements on postmortem human femurs. During recent years, however, an alternative stress model for the femur has been proposed that suggests functional adaptation of the skeleton and muscular forces lead to a moment-free loading of the femur (4,6,15), with uniform, axial compressive strain throughout the full length of the bone. The iliotibial band acts both as a lateral tension band and as a transmitter of a medially directed force due to the contact pressure at the greater trochanter, and it is thought to be the major contributor to the elimination of bending.

The aim of the present study was to perform *in vivo* strain measurements for the proximal lateral aspect of the femur of humans to determine whether the lateral femoral cortex is subjected to compression or tension during different exercises and to measure the magnitude of these strains.

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MATERIALS AND METHODS

Strain measurement for the proximal lateral aspect of the femur was performed as a part of the operation for "snapping hip syndrome" in two women, one 49 years old (Case 1) and the other 24 years old (Case 2). The right hip of each patient was operated on, and neither patient had other diseases of the hip or symptoms from the hips or the lower extremities. Radiographic examination showed a normal pelvis and normal hips in both patients. Measured on frontal radiographs of the hips with the patient in the standing position, the projected medial offsets of the femoral heads were 43 and 39 mm for Cases 1 and 2, respectively. The corresponding neck-shaft angles were 124 and 135°. The patients took part in the test after giving informed consent and after the experimental procedure was approved by the Ethical Review Committee at the University of Trondheim.

The components used for strain measurements were assembled and tested before surgery. The leads of the strain-gauge rosette (RY 91 3/120; Hottinger Baldwin Messtechnik [HBM], Darmstadt, Germany) were soldered to a terminal connected to a cable and a plug. The resistance (120 Ω) of the gauges was checked to verify electrical continuity. The rosette and soldering connections were protected with a polyurethane varnish (PU 120; HBM), and the insulation resistance of the gauges was checked with the rosette in a saline water bath (NaCl 0.9%) at 37°C. The unit consisting of the rosette, cable, and plug was sterilized in ethylene oxide gas (55°C) for 150 minutes. All fluid agents used for preparing the bone surface and for attaching the rosette were mechanically sterile-filtered with use of a pore

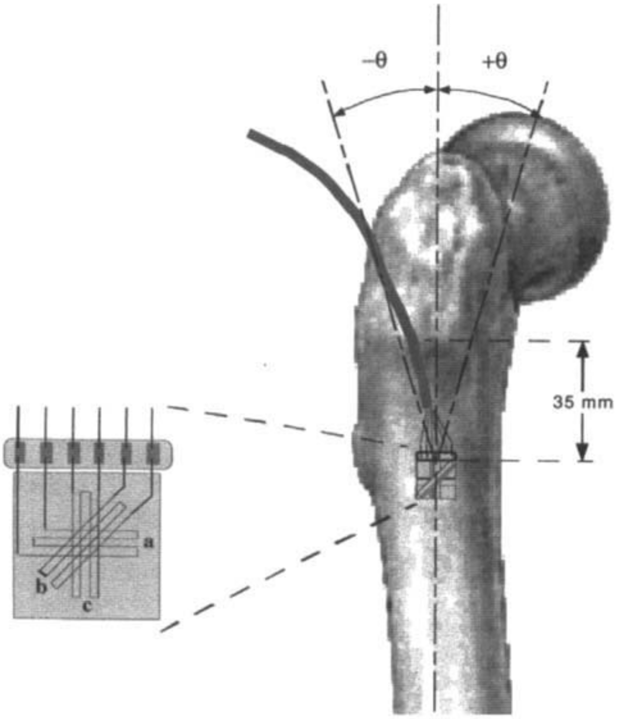

FIG. 1. Lateral view of the femur, indicating the site for attachment of the rosette. On the left is a close-up view of the rosette with the three grid elements (a, b, and c). +θ/–θ denotes the angle of the principle tensile strain, zero degree being parallel to the c-element of the rosette.

size of 0.22 μm (Sterivex-GV; Millipore, Bedford, MA, U.S.A.). The powder component of a two-component polymethylmethacrylate adhesive (X-60; HBM) used to bond the gauge to the bone was sterilized with γ-radiation.

The surgery was carried out with local anesthesia with use of 30 ml of 1% xylocaine/adrenaline (Astra, Södertälje, Sweden). The skin was incised longitudinally over the greater trochanter, and the fascia lata was split in the direction of the fibers. After the proximal insertion of the vastus lateralis was exposed, the fascia was split longitudinally for a length of 5-6 cm and the proximal lateral aspect of the femur was exposed with use of a periosteal elevator. A meticulous hemostasis was performed, and the soft tissues were covered with sponges to keep the femoral cortex dry and clean. The cortex was cleaned with saline, and, after drying, the surface was washed with diethyl ether. An etchant (Multipurpose Etchant; 3M, Minneapolis, MN, U.S.A.) was applied for 15 seconds and then rinsed off with saline. Finally, the cortical surface was again washed with diethyl ether before it was coated with a primer (Multipurpose Primer; 3M). The strain-gauge rosette was then bonded to the lateral aspect of the femur with use of the polymethylmethacrylate adhesive. The proximal border of the rosette was positioned 35 mm distal to the lateral eminence of the greater trochanter, and the c-element of the grids was aligned with the longitudinal femoral axis (Fig. 1). The wound was temporarily closed in layers, the wire cable exiting through the skin at the proximal end of the wound.

After closure of the wound, the patients were able to stand and to walk without limping. Strain recordings were obtained while the patient performed two-legged stance, single-legged stance, walking, and stair climbing. A force platform recorded ground reaction force. The leads of the strain gauges were connected to a signal amplifier (DMC Plus; HBM), and the strains were recorded at a frequency of 75 Hz with use of data acquisition software (DMC Lab; HBM). Strain values from the rosette elements were used to calculate the principal strains and their directions (8).

Strain recordings from the phases of unloading were used to determine the zero strain. According to Goodship (7), the minimum rate of change in strain occurs during the swing phase, and the swing phase was previously used to define the physiological level of zero strain in animal studies (11). For the one-legged and two-legged stance situations, zero strain was determined while the patient was lifting the involved limb off the floor. The same procedure was used when obtaining strain data for Case 2 during stair climbing. For Case 1, however, the method for determining zero strain for walking and that for stair climbing were different: zero strain was determined for walking during the swing phase and for stair climbing during the lift-off phase of gait.

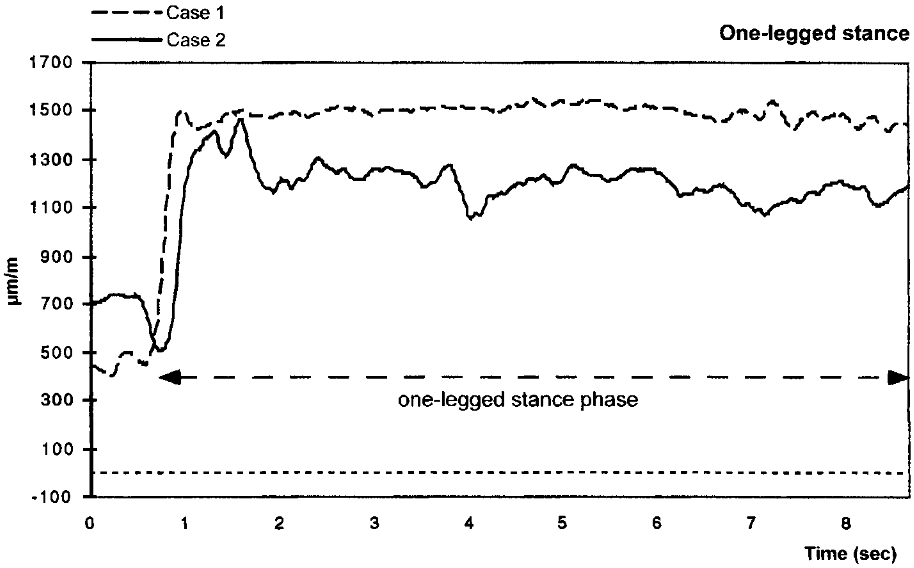

FIG. 2. Dynamic axial strain pattern during one-legged stance. The initial position of the patients was two-legged stance. After a sampling period of 1 second, the patients took a one-legged position, and a rapid increase in tension in the proximal lateral aspect of the femur was observed. During the rest of the stance, there were only minor fluctuations in the axial strain, probably reflecting the oscillating muscular forces involved in maintaining balance.

TABLE 1. *Average strain (μm/m) at the proximal lateral aspect of the femur during the plateau phases of four common physiological activities*

	Case 1				Case 2			
	Axial strain	Principal tensile strain	Principal compressive strain	θ[a]	Axial strain	Principal tensile strain	Principal compressive strain	θ[a]
Two-legged stance[b]	121	304	–347	32	378	494	117	–34
One-legged stance[b]	1,441	1,463	–435	6	1,196	1,225	–60	–9
Walking[c]	1,133	1,198	–393	12	—	—	—	—
Stair climbing[c]	1,113	1,454	–948	22	1,011	1,013	–194	–2

[a] θ denotes the angle, in degrees, between the longitudinal axis of the femur and the direction of the principal tensile strain.
[b] Mean values for a period of approximately 10 seconds of well balanced stance.
[c] Mean values (30 samples) during 0.4 seconds of the stance phase of three steps.

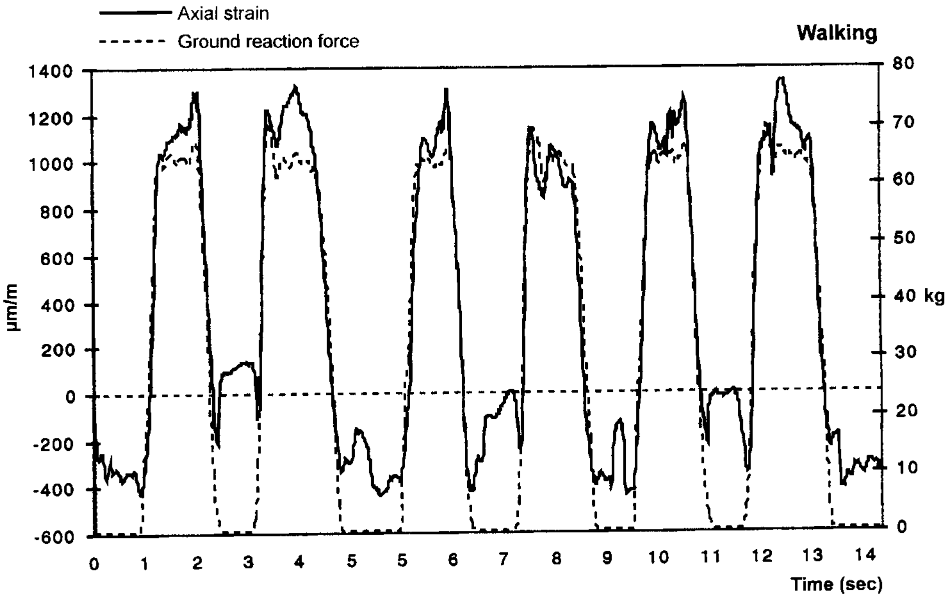

FIG. 3. Dynamic axial strain pattern during six walking cycles (Case 1). Also shown is the ground reaction force from the force platform.

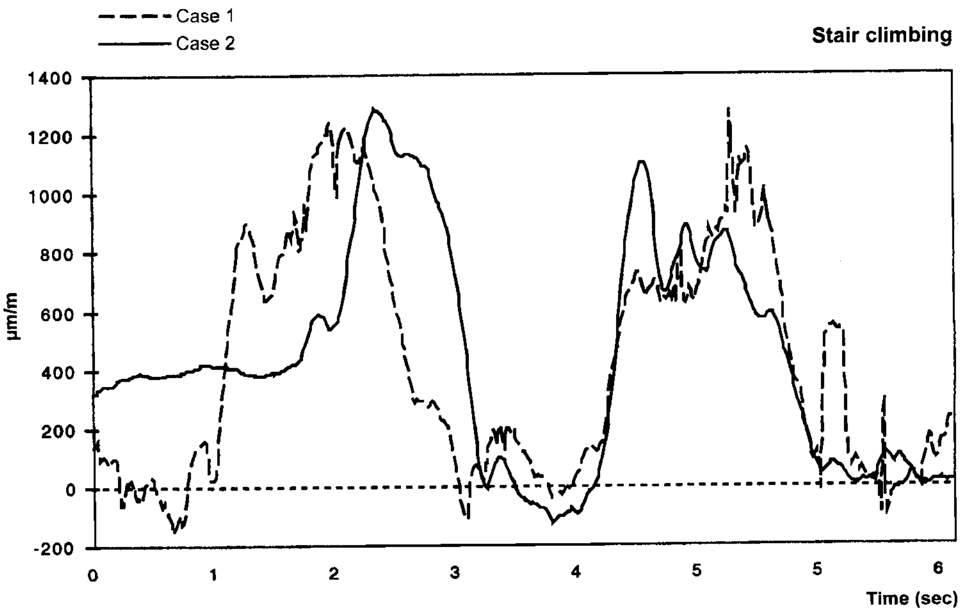

FIG. 4. Dynamic axial strain pattern during stair climbing.

After completion of the experiment, the cable from the rosette was cut close to the skin, the wound was reopened, and the rosette and the remaining particles of the polymethylmethacrylate adhesive were removed from the cortical surface. In both patients, the rosettes were still well fixed to the bone, and there were no signs of loosening or moisture between the rosette and the bone. Finally, a Z-plasty of the fascia lata was performed to treat the underlying disorder of the hip.

RESULTS

During two-legged stance, the principal tensile strains were significantly larger than the axial strains for both patients, indicating that the maximum tension was oblique to the long axis of the femur (Table 1). The principal tensile strains were 32 and −34° to the femoral axis; the opening angle was directed proximally (Fig. 1). When the patient placed all weight on the involved limb, the axial and principal tensile strains increased by approximately 1,000 μm/m. In both femurs, a similar and consistent change in the direction of maximum tension was seen; the principal tensile strain formed an angle of less than 10° to the femoral axis.

When the patients were walking or stair climbing, smaller changes in strain were seen, and the axial and principal strain values were comparable with the values measured during one-legged stance. However, compared with one-legged stance, a more pronounced change was seen in the principal compressive strains when the patients climbed a stair. In Case 1, the principal compressive strain increased from −435 to −948 μm/m; in Case 2, from −60 to −194 μm/m. It was also noted that the principal tensile strain was more oblique to the femoral axis in Case 1 (22°) than in Case 2 (−2°). The dynamic axial strain patterns during one-legged stance, walking, and stair climbing are depicted in Figs. 2, 3, and 4, respectively.

DISCUSSION

Recent investigations based on mathematical models (4,15), *in vitro* experiments (4), and finite element analyses (3,6) have challenged Pauwel's classic theory of hip biomechanics. According to these studies, the iliotibial tract acts as a lateral tension band that eliminates tension along the lateral aspect of the femur. However, numerous studies support the classic bending theory of the femur (2,7,10,13,14,16,19). Möser and Hein (15) calculated that the iliotibial band, due to its pressure against the greater trochanter, exerts a medially directed force of 1.4 body weight. With the forces in the external rotators added, the resultant force of the hip is aligned with the direction of the femoral neck axis. A similar principle of balancing muscular forces is applied in the theoretical argumentation for a bending-free loading of the femur distal to the trochanteric region (12).

Although the majority of the static and mathematical models favor the bending theory of the proximal aspect of the femur, there have been, to our knowledge, no studies published in which surface strains on human femurs have been measured. Therefore, neither biomechanical model of the hip has been validated with *in vivo* strain studies. To document the true nature of the strain at the external cortex of the proximal lateral aspect of the femur, we concluded that the optimum and most direct method would be to use strain gauges. The patterns of dynamic strain show that loading of the femur during normal activity leads to tension at the external cortex of the proximal lateral aspect of the femur. Furthermore, the principal tensile strain increased and aligned closer to the longitudinal axis of the femur during the stance phases than during unloading. Our results, therefore, support the theory that the upper femur is subjected to bending and that there is no functional lateral tension band or medially directed force sufficient to outweigh the bending moment imposed by the joint force. The magnitude of the principal tensile strains *in vivo* is comparable with that of the strains measured at corresponding locations *in vitro* with use of a loading configuration simulating the iliotibial tract (1,5).

To bond the rosettes to the femur, the proximal lateral aspect of the femur was exposed. Theoretically, the detachment of the proximal 5-6 cm of the vastus lateralis muscle could influence the strain in the underlying bone. However, we assumed that the effect on the strain measurements was negligible. Both the vastus lateralis fascia and the fascia lata were spilt longitudinally, and there were no discontinuities in the fasciae after temporary closure of the wound. After stepping down from the operating table, both patients had a normal gait pattern and had no pain or discomfort in the involved hip.

For both patients, we followed the same procedure for exposure, preparation and bonding of the strain-gauge rosette, and the acquisition of the strain data. However, the protocols differed for the determination of the zero strain level in the gauges. During the first operation, we determined the zero strain level while the patient was lying supine and relaxed on the operating table. When analyzing the data, we discovered a drift of the baseline measurement and, thus, the initial level of zero strain could not be used throughout the tests. Instead, strain data from the unloaded or swing phase before each test situation were used to tare the strain values. During the experiment, which lasted approximately 40 minutes, the drift of the strain measurements ranged from 100 (gauge a) to −1,300 μm/m (gauge c). During the second operation, we were aware of the possibility of drift in the strain outputs and determined the zero strain level in a standardized manner before each of the subsequent test situations. This must be taken into consideration when comparing the differences in femoral strain levels after the unloading and loading of an extremity that has been operated on.

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