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Mechanical loading of knee articular cartilage induced by muscle contraction can be assessed by measuring electrical potentials at the surface of the knee

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ABSTRACT

Electroarthrography (EAG) consists of recording electrical potentials on the knee surface that originate from streaming potentials within articular cartilage while the joint is undergoing compressive loading. The aim was to investigate how the contraction of specific leg muscles affects the contact force of the knee joint and, in turn, the EAG values.

For six normal subjects, voluntary isometric muscle contractions were repeatedly conducted to activate four leg muscle groups while the subject was lying on his back. Two EAG signals were recorded on the medial and lateral sides of the knee, as well as four EMG signals (gastrocnemius, hamstring, quadriceps, tensor fascia latae), and the signal from a force plate fixed against the foot according to the direction of the force.

The EAG and force signals were very well correlated: the median of the correlation coefficients between an EAG signal and the corresponding force signal during each loading cycle was 0.91, and 86% of the correlation coefficients were statistically significant ($p<5\%$). Isolated muscle contraction was possible for the gastrocnemius and hamstring, but not always for the quadriceps and tensor fascia latae. Using the clinical loading protocol which consists of a one-legged stance, the quadriceps and hamstring EMGs showed minimal activity; loading cycles with increased EAG amplitude were associated with higher EMG activity from the gastrocnemius, which is involved in antero-posterior balance.

These results document the role of the EAG as a "sensor" of the knee contact force and contribute to the development of clinical loading protocols with improved reproducibility.

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1. Introduction

Articular cartilage is a hydrated soft tissue covering the subchondral bone which provides a low friction, wear-resistant joint surface (Netti and Ambrosio, 2002). Cartilage degeneration, known as osteoarthritis (OA), can cause pain, stiffness, and loss of mobility of the joint. Techniques based on clinical symptoms, imaging and biomarkers, are currently applied to diagnose OA (Bijlsma et al., 2011). Cartilage degradation can develop over decades and methods are currently lacking for detecting early stage OA, which could help prevent, or even reverse cartilage degradation (Chu et al., 2012).

The extracellular matrix of articular cartilage is composed of proteoglycan trapped in a collagen network. Due to its negatively charged glycosaminoglycan (GAG) side chains, proteoglycan attracts mobile cations in the fluid (Kim et al., 1995). Under equilibrium conditions, excess cations distribute around GAGs symmetrically. When mechanically loaded, interstitial fluid flow drags the excess cations and separates them from the fixed negatively charged proteoglycan groups, thereby generating an electrical field. This load-induced electrical field, called streaming potentials, could serve as a sensitive indicator of collagen integrity and proteoglycan loss (Buschmann and Grodzinsky, 1995; Frank et al., 1987; Armstrong et al., 1984). It has been shown *in vitro* that the sensitivity of these electromechanical characteristics to early stages of degradation is higher than purely mechanical, biochemical or histological properties (Garon et al., 2002; Légaré et al., 2002; Buschmann et al., 1999; Bonassar et al., 1995). Recently, a novel non-invasive technique called electroarthrography (EAG) was proposed to assess articular cartilage and diagnose OA by measuring load-induced electrical potentials at the surface of the knee. The knee is mechanically loaded as the upright subject shifts his weight from one leg to the other. A clinical study comparing normal subjects, OA patients and patients with total knee replacement, modeling studies and animal studies has supported the

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hypothesis that EAG signals originate only from articular cartilage and reflect the forces applied to the cartilage and its state of degradation (Préville et al., 2013; Han et al., 2014; Changoor et al., 2014).

The amplitude of the streaming potentials depends on cartilage integrity, but also on the loading conditions. Direct measurement of the knee joint contact force has long been impracticable due to technical limitations. Computer simulations have thus been carried out to calculate the contact force using musculoskeletal models (Shelburne et al., 2005; Adouni et al., 2012). With the development of instrumented knee implants, *in vivo* loading measurement became applicable. It was found that the contact force measured *in vivo* during a one-legged weight bearing stance, which is similar to the EAG loading technique, ranged from 2 to 3 times the body weight (Kutzner et al., 2010). Being aware of the possible role of muscle forces, we hypothesized that muscle contraction can modify the contact force and, in turn, the EAG values. The aim of this study was to test this hypothesis so as to document the role of the EAG as a "sensor" of the knee contact force and also, to contribute to the development of new EAG loading protocols with improved reproducibility.

2. Methods

Six healthy subjects without any relevant injuries were recruited to participate in this study (Table 1). The experimental protocol was approved by the Research Ethics Board of our institution. Before the experiments, each subject was instructed with respect to the experimental protocol and signed an informed consent form.

To characterize the relationship between muscle contraction and EAG, voluntary isometric muscle contractions were conducted to activate specific leg muscles while the subject was lying on his back, this position ensured that the knee was minimally loaded. Electromyogram signals (EMG) were recorded to document specific muscle activities while a force plate was used to measure the force applied by the foot. The stability of the knee being predominantly maintained by the quadriceps, hamstring and gastrocnemius (Winby et al., 2009), these three muscle groups were investigated (Fig. 1). We also investigated the tensor fasciae latae (TFL), which is activated to keep balance when the opposite foot is lifted (Saladin, 2004). Prior to the recordings, the subjects practiced voluntary contractions. During the recordings, the subject repeated each contraction ten times for averaging purposes; each isometric contraction lasted for 1–2 s, followed by a 10 s rest period to avoid cumulative fatigue. Finally, a knee loading protocol similar to the clinical protocol used previously was applied (Préville et al., 2013), with the erect subject shifting his weight from a two-legged stance to a one-legged stance.

An 8-channel wireless acquisition system (Bioradio 150, Clevemed Medical Inc.) was used to measure 2 EAG, 5 EMG and 1 force signal. The EAG and force signals were amplified with DC coupling whereas the EMG signals were amplified with AC coupling; the sampling rate was 600 Hz with a resolution of 16 bits. The EMG bipolar electrodes were positioned according to the SENIAM standard (Hermens et al., 2000) over the gastrocnemius medialis (GM) and the gastrocnemius lateralis (GL) from the calf, the biceps femoris long head (BF) from the hamstring, the rectus femoris (RF) from the quadriceps, and the TFL on the line from the anterior spina iliaca superior to the lateral femoral condyle in the proximal 1/6. Five pairs of electrodes with an inter-electrode distance of 35 mm were thus positioned, parallel to the direction of muscle fibers. As for the EAG measurements, two electrodes were positioned on the lateral and medial sides of the knee over the joint line which was determined by palpation; a reference electrode was placed over the middle of the tibia and a ground electrode was placed just below. Self-adhesive electrodes (Red Dot, 3 M) were used and the skin under the electrode was prepared with an abrasive paste (Nuprep) to reduce the skin-electrode impedance. A force plate (FP-BTA, Vernier) measured the force applied by the foot during muscle contraction, and its position varied according to each muscle.

Table 1
Characteristics of the subjects

Subject	Gender	Weight (kg)	Height (cm)	Age
1	M	78	165	43
2	F	52	158	21
3	M	83.6	188	63
4	F	60	166	29
5	M	77	185	32
6	F	64	173	20
Mean ± SD		69.1 ± 12.3	172.5 ± 11.9	34.7 ± 16.2

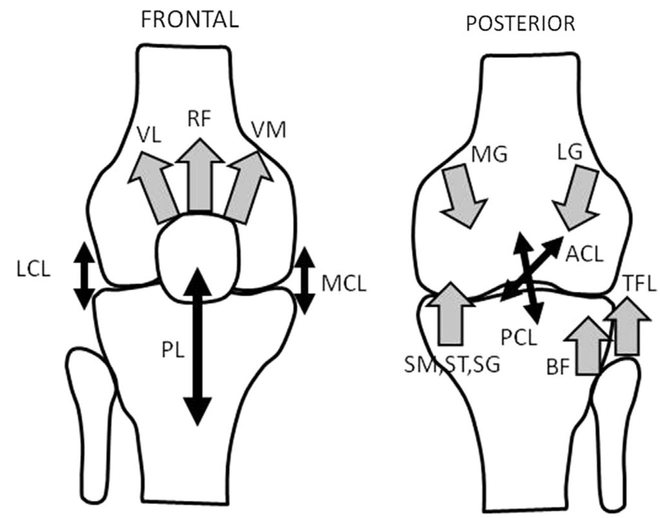

Fig. 1. Schematic representation of some forces acting on the knee joint. The base of the gray arrows indicates the approximate insertion point of the muscles, whereas the arrows point in the direction of the acting force. The thinner double arrows represent the ligaments. Frontal view: vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), tensor fasciae latae (TFL), patella tendon (PT), lateral collateral ligament (LCL), medial collateral ligament (MCL). Posterior view: medial gastrocnemius (MG), lateral gastrocnemius (LG), biceps femoris (BF), semimembranous (SM), semitendinosus (ST), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL).

Signal processing was carried out using user-written software (Matlab). First, the EAG and force signals were low-pass filtered (5 Hz) to reduce noise and 60 Hz interference. Second, the DC drift of the EAG signals originating from electrode and amplifier offset potentials was eliminated by subtracting from the measured signals the baseline defined by a third order polynomial for each cycle. For the EMG signals, the average of the two signals from the gastrocnemius was first computed. The four EMG signals were then high-pass filtered (20 Hz) and fully rectified. A low-pass filter (5 Hz) was finally used to compute the envelope.

The following statistical procedures were applied. The Pearson's correlation coefficients between the EAG signal and the concomitant force signal were computed using all the samples during each contraction cycle. A total of 480 correlation coefficients were thus computed. Also, average values during each cycle for the EAG, EMG and force signals were computed during the time interval for which the force signal was above 90% of the maximum force observed during the cycle. The values from the 10 cycles were then averaged, representing each of the eight channels for each subject. A one way analysis of variance with the muscle group as a factor was applied for each of the eight variables to test the influence of the muscle group. A post hoc Student's t test was then used to compare specific variables. Statistical significance was tested at the $p < 0.05$ level.

3. Results

Representative EAG, EMG and force measurements during the isolated contraction of each of the four muscle groups are shown in Figs. 2–5. Results for the gastrocnemius contraction are shown in Fig. 2. The force plate was fixed against the sole of the foot (Fig. 2, top right). The supine subjects pointed their forefoot away so that a force was applied by the plantar flexion of the foot and then came back to the initial position after 1–2 s. The medial and lateral heads of the gastrocnemius develop from the medial and lateral condyles of the femur separately. Thus, when the gastrocnemius is contracted, the muscle group pulls the femur toward the tibia, which increases the contact force acting on the cartilage (Fig. 2, top left). The EAG and force signals increase and decrease simultaneously with the EMG signal (Fig. 2, middle). The bottom panel of Fig. 2 shows that an EMG signal was only observed in the gastrocnemius channel.

Data acquired during hamstring contraction is shown in Fig. 3. The force plate was placed on the table, under the heel (Fig. 3, top

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