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Electrical potentials measured on the surface of the knee reflect the changes of the contact force in the knee joint produced by postural sway

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ABSTRACT

Electroarthrography (EAG) is a novel technique for recording potentials on the knee surface that are generated by the compression of articular cartilage and that reflect both compression force and cartilage quality. The mechanical loading of the knee is achieved by transferring the subject's body weight from a bipedal stance to a unipedal stance. We hypothesized that EAG potentials change with postural sway. The study was performed on 20 normal subjects (10 male, 10 female; age 29 ± 10.5 yrs.; mass 68.8 ± 14.2 kg; height 172.6 ± 11.4 cm). Data was recorded during 10 successive loading cycles repeated on two different days. During loading, EAG potentials were recorded with 4 electrodes placed on both sides of the knee and the ground reaction force (GRF) and the antero-posterior and medial-lateral displacements of the center of pressure (COP) were measured with a force plate. Two electromechanical models predicting the EAG signal from the GRF alone or from the GRF plus the COP displacements were computed by linear regression. The mean relative error between the four EAG signals and the predicted signals ranged from 24% to 49% for the GRF model, and from 15% to 35% for the GRF + COP model, this reduction was statistically significant at 3 electrode sites ($p < 0.05$). The GRF + COP model also improved the repeatability of the parameters estimated on the first and second days when compared to the GRF model. In conclusion, EAG signals can be predicted by GRF and COP displacements and may reflect changes in the knee contact force due to postural sway.

1. Introduction

Electroarthrography (EAG) is a novel technology which consists of recording electrical potentials using electrodes applied on the surface of the knee during mechanical loading of the knee joint. A clinical study comparing normal subjects, osteoarthritis patients and patients with total knee replacement [1], a finite element modelling study [2] and animal studies [3,4] have supported the hypothesis that EAG signals reflect the forces applied to the cartilage and its state of degradation. These EAG signals are generated by the relative displacement of ions against the fixed charge density within the cartilage that is induced by the hydrostatic pressure gradient during compression, this displacement produces "streaming potentials" that can be recorded directly on the cartilage surface and that are decreased in degraded cartilage [5–7].

To mechanically load the knee during the EAG recordings, the subjects stand on both legs, then slowly transfer their body weight to their instrumented leg for a few seconds and finally return to the bipedal stance. The EAG signals are not constant during this unipedal stance, which suggests that the cartilage is compressed not only by the constant body weight applied on the leg during the unipedal stance. Indeed, measurements using instrumented knee implants have shown that the knee contact force measured *in vivo* during a unipedal weight bearing stance, which is similar to the EAG loading technique, ranges from 2 to 3 times the body weight [8]. This additional force can be attributed to the muscular activity developed by postural balance [9–11].

Direct assessment of these muscle forces is challenging. Since postural sway is closely related to muscle activity, monitoring the displacement of the center of pressure (COP) of the subjects during the unipedal stance can provide useful information [12,13]. In

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biomechanics, the COP refers to the location of the vertical ground reaction force (GRF) vector which can be directly measured with a force platform [11]. It has been suggested that COP is particularly relevant to the biomechanical study of balance and postural control [14,15] and that COP excursions can be used as a good indicator of the postural stability of individuals [16].

We hypothesized that the EAG potentials change with postural sway. Two electromechanical models predicting the EAG signal as a function of the ground reaction force and the orthogonal displacements of the COP were thus built to investigate the source of the EAG variations. Accounting for these variations can ultimately contribute to the development of optimized EAG measurement protocols with improved repeatability for the clinical assessment of cartilage degradation.

2. Methodology

2.1. Experiments

Twenty healthy volunteers without any relevant orthopedic injuries (10 male, 10 female; with age 29 ± 10.5 y.o.; weight 68.8 ± 14.2 kg; height 172.6 ± 11.4 cm) were recruited. The experimental protocol was approved by the Research Ethics Board of Polytechnique Montréal. Before the experiments, each subject was informed of the experimental protocol and then signed an informed consent form.

The EAG technique has been validated with different approaches. In a clinical study [1], EAG potentials of normal subjects were greater than those of patients with Osteoarthritis, thus demonstrating that EAG reflects cartilage degradation; also, EAG potentials overlying total knee replacement prostheses were statistically null, supporting the hypothesis that EAG signals are generated by compressed articular cartilage and not by other sources such as muscles, tendons, ligaments, bones, skin. Finite element models [2] accurately reproduced the EAG potential distributions measured over the knee, supporting the hypothesis that EAG signals originate within the lateral and medial compartments of the knee joint. In animal studies, EAG signals from the fetlock joint of horses indicated that EAG signals were sensitive to cartilage degradation and correlated with the applied force and the streaming potentials measured directly on the cartilage [3,4].

In this study, self-adhesive disposable electrodes (3M Red Dot) were used to measure the EAG signals from both sides of the knee of the dominant leg which was determined by the one-two step test: two electrodes were placed side by side on the medial side and two on the lateral side over the joint line which was determined by palpation (Fig. 1). The reference electrode was positioned over the middle of the tibia and a ground electrode was placed just below it. Before placing the electrodes, hair was shaved if necessary, and the skin under the electrode was cleaned with an abrasive paste (Nuprep) to reduce the skin-electrode impedance. An 8-channel portable wireless acquisition system (Bioradio 150, Clevemed Medical Inc., Cleveland, OH) was used to digitize the 4 EAG signals. These EAG signals and the 4 force signals described in the following paragraph were recorded simultaneously on a personal computer using custom designed software (LabView). A test-retest protocol was performed by having all the subjects complete the same measurement sequence on a subsequent day to evaluate the EAG repeatability.

During the EAG measurements, a Nintendo Wii Balance Board (WBB) was placed under the foot of the instrumented leg to record the GRF. The WBB has been increasingly used as a force plate for assessing postural control because it is inexpensive, portable and accurate [17], it exhibits excellent test-retest reliability for COP assessment and is being used to estimate standing balance in a clinical setting [18,19]. The WBB has four uniaxial vertical force transducers located at the four corners and the COP can be calculated (cm) along the anterior-posterior axis ($COP_{A/P}$), as well as along the medial-lateral axis ($COP_{M/L}$) with the following equations:

$$COP_{A/P} = \frac{L}{2}\frac{((TR + TL) - (BR + BL))}{TR + TL + BR + BL} \quad (1)$$

$$COP_{M/L} = \frac{W}{2}\frac{((TR + BR) - (TL + BL))}{TR + TL + BR + BL} \quad (2)$$

Where the board dimensions are $L = 43.3$ cm and $W = 22.8$ cm, and TR, TL, BR and BL are the forces (kg) measured at the four corners of the WBB using the nomenclature shown in Fig. 1.

A wooden board with the same height was placed under the other foot to help maintain balance during weight shifting. The subjects initially stood motionless on both legs, with their feet shoulder-width apart. Then, they slowly transferred their body weight on the instrumented leg to compress the cartilage while the contralateral foot stayed in contact with the floor. Finally, the subjects went back to the initial position. During this process, the subjects tried to keep their balance as best as possible. Each loading cycle lasted about 10 s. Ten loading cycles were repeated for averaging purposes.

Signal processing was carried out on a personal computer using user-written software (Matlab) [1]. The EAG and force signals were initially filtered with a low-pass filter having a cut-off frequency of 5 Hz to eliminate electromyographic interference. Then, the DC

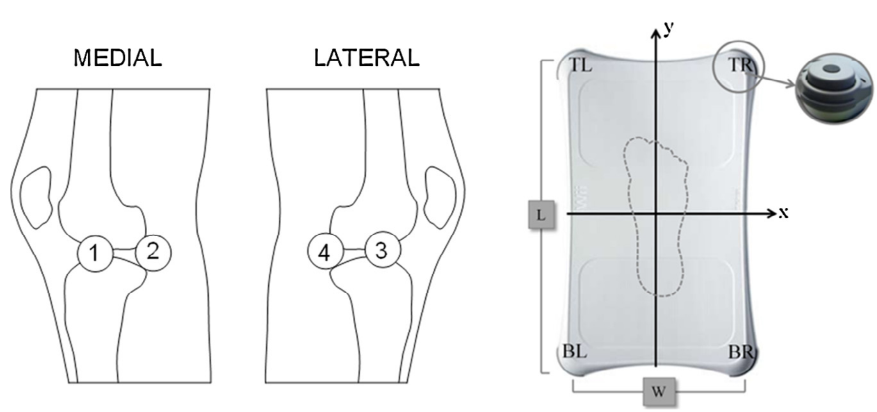

Fig. 1. Left panel: position of the 4 electrodes on the surface of the knee. Right panel: coordinate system and force transducers of the Wii Balance Board. The foot was placed within the dashed outline and the COP was calculated using the center of board as the origin. Four transducers at each corner are identified as top left (*TL*), top right (*TR*), bottom left (*BL*) and bottom right (*BR*). The antero/posterior movement corresponds with the *y* axis, and the medial/lateral movement corresponds with the *x* axis.