ARTICLE IN PRESS

Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Decrease of the electrical potentials measured on the surface of the knee and produced by cartilage compression during successive loading cycles

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ARTICLE INFO

Article history:
Accepted 8 September 2016

Keywords:
Knee joint
Cartilage
Streaming potentials
Electroarthrography
Modeling

ABSTRACT

Electroarthrography (EAG) is a new technique for measuring electrical potentials appearing on the knee surface during loading that reflects cartilage quality and joint contact force. Our objective was to investigate the evolution of EAG signals during successive loading cycles. The study was conducted on 20 standing subjects who shifted their body weight to achieve knee loading. Their EAG signals were recorded during 10 successive loading cycles, and during a subsequent sequence of 10 cycles recorded after a 15 min exercise period. Multiple linear regression models estimated the electro-mechanical ratio (EMR) interpreting the ability of cartilage to generate a certain potential for a given ground reaction force by taking into account this force and the center of pressure displacements during unipedal stance. The results showed that the EMR values slowly decreased with successive cycles: during the initial sequence, the correlation coefficients between EMR values and sequence numbers were significant at 3 of the 4 electrode sites ($p < 0.05$); for the post-exercise sequence, the EMR values still decreased and were significantly lower than during the initial sequence ($p < 0.001$). The reduction of EMR values could arise from muscle activity and habituation of the stretch reflex, and also from the time dependent electromechanical properties of cartilage. In conclusion, refraining from physical activity before the EAG measurements is important to improve measurement repeatability because of the EMR decrease. The electromechanical model confirmed the role of EAG as a natural sensor of the changes in the knee contact force and also improved EAG measurement accuracy.

1. Introduction

Electroarthrography (EAG) is a novel technique for measuring the load-induced streaming potentials at the surface of knee that are generated by articular cartilage. Streaming potentials arises from the movement of electrolyte ions in the liquid phase relative to charge groups that are fixed to the cartilage extracellular matrix under dynamic compression (Paolo and Netti, 2007). *In vitro* studies have shown that lower streaming potentials indicates cartilage degeneration (Frank, et al. 1987; Légaré et al., 2002). We previously demonstrated in simulations, animal studies and a clinical study that load-induced electric potentials can also be detected at the surface of the knee and can potentially be used for the non-invasive assessment of Osteoarthritis (Préville et al., 2013; Han et al., 2014; Changoor et al., 2014).

Although a test-retest protocol demonstrated that clinical EAG measurements are repeatable (Préville et al., 2013), some EAG variability can still be observed within individuals, which can hinder its clinical application for cartilage quality assessment. During clinical EAG measurements, joint loading is achieved by having the subjects slowly shift their weight from a bipedal stance to a unipedal stance. The regulation of balance during weight shifting involves muscular activities by which the knee contact force can also be influenced (Adouni et al., 2012). Indeed, the knee contact force that has been measured *in vivo* is two to three times the body weight during the unipedal stance (Kutzner et al., 2010). By monitoring electromyograms (EMG) of the knee flexor and extensor muscles during EAG measurements, we also observed that knee flexors and extensors are activated during weight shifting to maintain balance (Zhu et al., 2016). Thus, muscular activity associated to body sway can contribute to the EAG variability.

To improve our understanding of EAG signals and contribute to the development of reliable EAG techniques for cartilage quality assessment, an electromechanical model that takes into account

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http://dx.doi.org/10.1016/j.jbiomech.2016.09.008
0021-9290/

the changes in knee contact force due to body sway was developed and the evolution of the EAG signals during successive loading cycles was investigated.

2. Methodology

The protocol was approved by the Research Ethics Board of Polytechnique Montréal. Each subject was initially informed of the study and then signed an informed consent form. The study comprised 20 subjects (10 males, 10 females), with age 28.5 ± 10.7 y.o., height 172.7 ± 11.4 cm, weight 67.5 ± 14.4 kg. None of the participants reported knee injury or symptomatic abnormalities.

Self-adhesive disposable electrodes (Red Dot™, 3M) were used to measure the EAG signals. The electrodes were positioned over the joint line of the knee on the dominant leg. The joint line was determined by palpation. Four electrodes were distributed over the medial and lateral sides. A reference electrode was positioned at the middle of the frontal tibia and a ground electrode was placed below it. Skin preparation with an abrasive paste (Nuprep) was performed at all electrode sites to minimize epidermal impedance before placing the electrodes. Hair was shaved if necessary.

The subjects were informed not to do any strenuous physical exercise before the experiments. The subjects stood barefoot with their feet shoulder-width apart, keeping their legs straight. To mechanically load the cartilage, the subjects swung slowly to transfer their body weight to the measured leg for 3–4 s, then they came back to their initial position. A Nintendo Wii Balance Board (WBB) was placed under the foot of the measured knee to record the four vertical forces at the corners of the board. The WBB is being increasingly used as a force plate for assessing postural control because it is inexpensive, portable, reliable and accurate (Bartlett et al. 2014). A wooden plate was placed under the other foot to maintain normal balance. Each subject practiced the weight shifting procedure before EAG capture (3–5 cycles). Ten consecutive loading sequences were recorded. Hereafter, to determine whether the results could be reproduced and investigate the possible role of prior physical activity, the subjects continued the weight shifting exercise for about 15 min. Once this exercise was completed, 10 more consecutive loading sequences were documented.

2.1. Data acquisition and processing

The EAG and force signals were recorded with a portable wireless acquisition system (Bioradio 150, Clevemed). These DC signals were sampled at 600 Hz with a resolution of 16 bits. Signal processing was carried out using user-written software (Matlab). All EAG and force signals were initially low-pass filtered (5 Hz) to reduce possible high frequency components such as EMG, noise and 60 Hz interference. Afterwards, the DC drift of EAG and force signals, originating from electrode polarization and amplifier offset potential, was corrected as follows. The operator manually selected points prior to and after each loading cycle. A third degree polynomial was used to reconstruct the baseline based on the selected values and subtracted from the filtered EAG and force signals. This procedure was repeated for all the loading cycles.

2.2. EAG modeling

Since streaming potentials are associated with loading conditions, the term *electro-mechanical ratio* (EMR: μV/kg) was introduced to describe the ability of the cartilage to generate a certain potential for a given force (Schmidt-Rohlfing et al., 2002; Changoor et al., 2013). The knee contact force that compresses the cartilage during loading is difficult to measure. It incorporates not

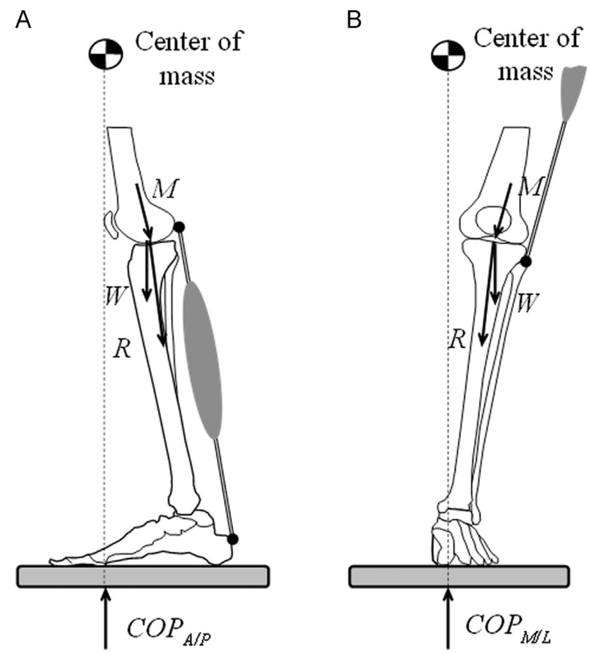

Fig. 1. Knee loading during unipedal stance. The gray rectangles represent the force plate. A) Sagittal plane: *W*, part of the body weight supported by the knee; *M*, force by the gastrocnemius pulling on the condyles of the femur to maintain equilibrium; *R*, resultant of *W* and *M* passing through the mechanical axis; $COP_{A/P}$, position of the center of pressure along the antero-posterior axis, B) Coronal plane: *W* and *R*, same as above; *M*, force generated by the tensor fasciae latae and gluteus maximus muscles and pulling on the iliotibial band which is anchored on the lateral condyle of the tibia to maintain equilibrium; $COP_{M/L}$, the position of the center of pressure along the medial-lateral axis.

only the ground reaction force (GRF), but also the muscle forces that maintain the balance. Thus, when the center of mass of an upright subject moves anteriorly, the tendons of the gastrocnemius muscles pull on the condyles of the femur to maintain balance, which increases the knee contact force (Fig. 1A). Similarly, when the center of mass moves medially, a force generated by the tensor fasciae latae and gluteus maximus muscles pulls on the iliotibial band which is anchored on the lateral condyle of the tibia, which again increases the contact force (Fig. 1B). The center of pressure (COP) displacement is thus associated with the muscle forces acting on the knee joint. Therefore, an electromechanical model was developed to predict the EAG signal from the GRF and the COP displacements. These displacements (cm) can be calculated from the WBB data 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* (top right), *TL* (top right), *BR* (bottom right) and *BL* (bottom left) represent the forces (kg) measured at each corner of the WBB. Finally, the $EAG(t)$ signal measured at a given time can be modeled as a linear combination of the ground reaction force $GRF(t)$, and the muscular forces represented by the displacements of the COP along both antero-posterior and medial-lateral directions.

$$EAG(t) = EMR \bullet GRF(t) + \beta \bullet COP_{A/P}(t) + \gamma \bullet COP_{M/L}(t) + \varepsilon \quad (3)$$

The coefficients *EMR*, β and γ are estimated by multiple linear regression using all the *EAG, GRF*, $COP_{A/P}$ and $COP_{M/L}$ samples recorded during a loading cycle. The coefficient ε represents