Yonsei Medical Journal
Vol. 43, No. 5, pp. 637 - 643, 2002

Evaluation of a Bio-impedance Method for Measuring Human Arm Movement

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This study proposes a new method for measuring upper limb movement using a bio-impedance technique. Bio-impedance and joint angle were simultaneously measured during the wrist and elbow movements of 12 normal subjects. The joint angles of the wrist and elbow were estimated by measuring the bio-impedances of the forearm and upper arm, respectively. Although the measured bio-impedances on upper limbs varied among individuals, changes in the bio-impedances and joint angles of the wrist and elbow during their extension and flexion were very highly correlated, having correlation coefficients of 0.96 ± 0.04 and -0.98 ± 0.02, respectively. The reproducibilities of wrist and elbow bio-impedance changes were $2.1 \pm 1.0\%$ and $1.8 \pm 1.0\%$, respectively. Since the proposed method is not restricted by size or the duration of measurements, it is expected to be useful for the analysis of athletic movement.

Key Words: Bio-impedance, bio-dynamics, upper limb movement, wrist angle, elbow angle

INTRODUCTION

Research on human movement analysis has been focused primarily on movements of the lower limb, for which, goniometry, video analysis, force plates, and electromyography (EMG) have been used.[1-3] Of these methods, the goniometer offers the most accurate way of measuring movement. The goniometer is attached to a joint and its angle is directly measured. However, continuous measurement is difficult to measure in this way and the goniometer is also inappropriate for the measurement of rapid movement.[3] The video analyzer and the force plate are large in scale and can only be used in places where equipments are installed. Alternatively, there are pressure gauges in the form of shoes, which measures pressure distribution such as the force plate. This kind of pressure gauge requires each subject to have shoes prepared according to foot size, and it is inappropriate for upper limb movement analysis. In contrast to this device, EMG is useful for observing the origin of such movements, by examining the state or activity of a muscle rather than by obtaining information about some body movement. However, EMG is inappropriate for the measurement of joint angle over a long time.

In general, bio-impedance noninvasively offers valuable information about the internal environment of the organism.[4] Due to its noninvasiveness, bio-impedance has been widely applied in clinical medicine for some time, but in biomechanical field, it was not applied much until 1992 when Nakamura et al. used bio-impedance instead of EMG.[3] In their experiment, a strong relationship was found between the rate of change of forearm impedance and the angular velocity of the elbow joint (correlation coefficient=-0.97).[3] These results proposed the possibility of using bio-impedance changes for observing a movement pattern. However, the above study only used joint angular velocity and the rate of bio-impedance change, and did not report upon the relationship

Received July 22, 2002
Accepted August 26, 2002

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between changes of joint angles and bio-impedance.

In our study, a 2-channel bio-impedance measurement system was built to measure impedance changes of the wrist and elbow movements and the relationships between the joint angles and bio-impedances were obtained. Because the measured impedance is dependent upon individuals and electrode location, repeated measurements were taken on the same person in order to evaluate the reliability of the proposed method.

MATERIALS AND METHODS

Bio-impedance model of the upper limb

A major factor influencing bio-impedance change is change in the cross section of muscle, as shown in Fig. 1. As the voltage between the voltage-sensing electrodes is determined by Ohm's law (Eq. (1)),[4-7] the measured voltage enables one to obtain the impedance because the current is constant. According to Eq. (1), the voltage (impedance) is proportional to muscle resistivity (P_m) and the distance (L), and is inversely proportional to the cross-sectional area of the muscle (A_m). Muscles such as the extensor carpi muscle and the flexor carpi muscle, which are attached to the radius and ulna, determine wrist movement.[8,9] And similarly, elbow movement is determined by the biceps and triceps.[8,9] Therefore, bio-impedance changes caused by change in the cross-sectional areas of these muscles during movement can be measured using surface electrodes.

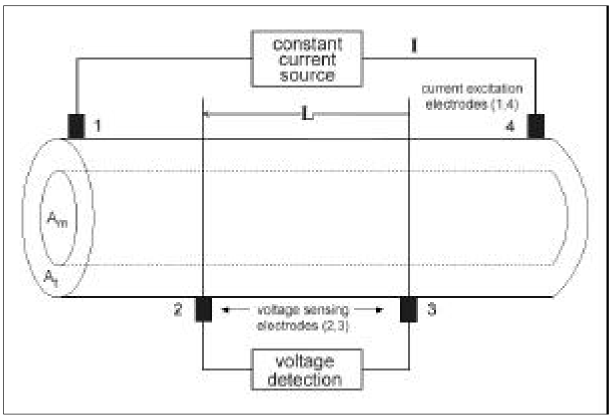


Fig. 1. Two compartment model of upper limb used for measuring impedance change.

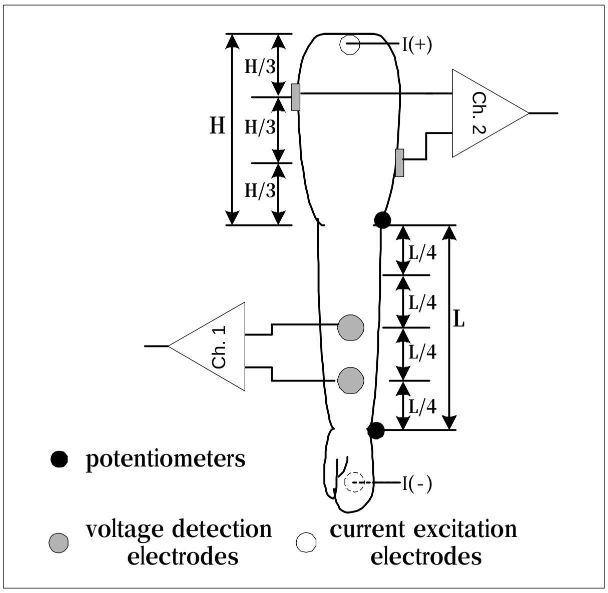
$$V = I(Z_m // Z_t) = I(r_m \frac{L}{A_m} // r_t \frac{L}{A_t}) \quad (1)$$

V : Potential between voltage - sesnsing electrodes 2 and 3 [V]
I : Constant current [mA]
L : Distance between voltage - sensing electrodes [cm]
A_m : Cross - sectional area of muscle between electrodes 2 and 3 [cm^2]
A_t : Cross - sectional area of tissue other than muscle [cm^2]
r_m : Muscle resistivity [$\Omega \cdot cm$]
r_t : Tissue resistivity [$\Omega \cdot cm$]

Electrode configuration

In Fig. 2(a), current excitation electrodes were attached so that a constant current (300 uA, 50 kHz) could flow from the shoulder (I+) to the back of the hand (I-). Channel 1 was connected to the voltage electrode pair on the forearm and the impedance changes caused by wrist movement were measured. Channel 2 was connected to the voltage electrode pair on the upper arm and impedance changes caused by elbow movement were measured. Disposable Ag-AgCl (RedDot, 3M, USA) electrodes with a diameter of 10 mm were used as voltage and current electrodes. Fig. 2(b) shows a photograph of our experiment and includes the electronic goniometer built for this study.

If the directions of the voltage electrode pair and current flow become perpendicular, impedance cannot be measured. This fact should be considered when selecting the appropriate pairs of the voltage electrodes. Also, the relationship between the change of the muscle's cross-sectional area due to extension and flexion of wrist and elbow, and the impedance change due to these changes in muscles is not linear.[3] Therefore, electrodes should be placed at locations where changes in bio-impedance and joint angle are well represented in order to accurately evaluate upper limb movement using an impedance method. The optimal electrode location satisfying the above requirements was found during our previous study, and was used in this study.[10,11]



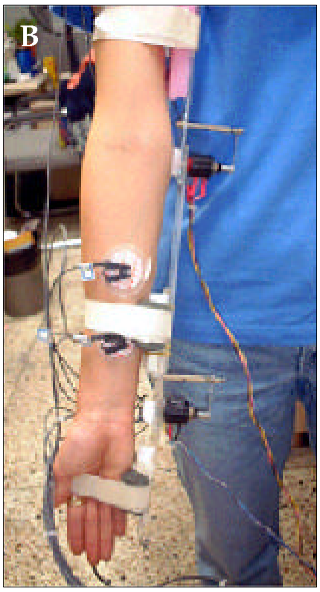


Fig. 2. Electrode configuration and potentiometers on the wrist and elbow (A) and their photograph (B).

Analysis of upper limb movements

Movements of the body are due to changes in the muscular-skeletal system, and these are diverse and complicated, especially in the limbs. Upper limb movements include extension, flexion, hyperextension, and circulation of the wrist, extension and flexion of fingers, extension and flexion of elbow, supination and pronation of upper limb.[8-9] Of these diverse movements of the upper limb, this study analyzed only the two basic movements shown in Fig. 3, namely, wrist and elbow movements, with extension or flexion of the fingers.

To analyze wrist movements, all of the joints of the upper limb were held in extension while the wrist joint was moved from extension (0 degrees) to flexion (70 degrees). To analyze the elbow movement, the elbow joint was moved from extension (0 degrees) to flexion (105 degrees). The angles of the wrist and elbow joints, and the impedances were measured simultaneously using a goniometer and an impedance system. In order to confirm the usefulness of the proposed method, its reproducibility was evaluated and correlation coefficients were obtained between changes in terms of the angles of wrist and elbow joints and corresponding impedance changes in 12 normal subjects.

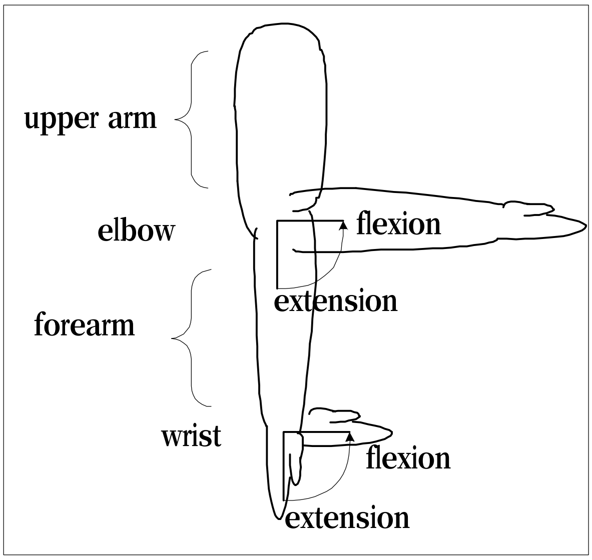


Fig. 3. Upper limb movements analyzed in this study.

RESULTS

Wrist movement

Fig. 4 shows the angular change of the wrist (A) and the impedance change of the forearm (B) for wrist movement with elbow extension. The impedance change was measured between the electrode pair on the forearm from Ch 1 in Fig. 2. In Fig. 4(B), impedance increased when the

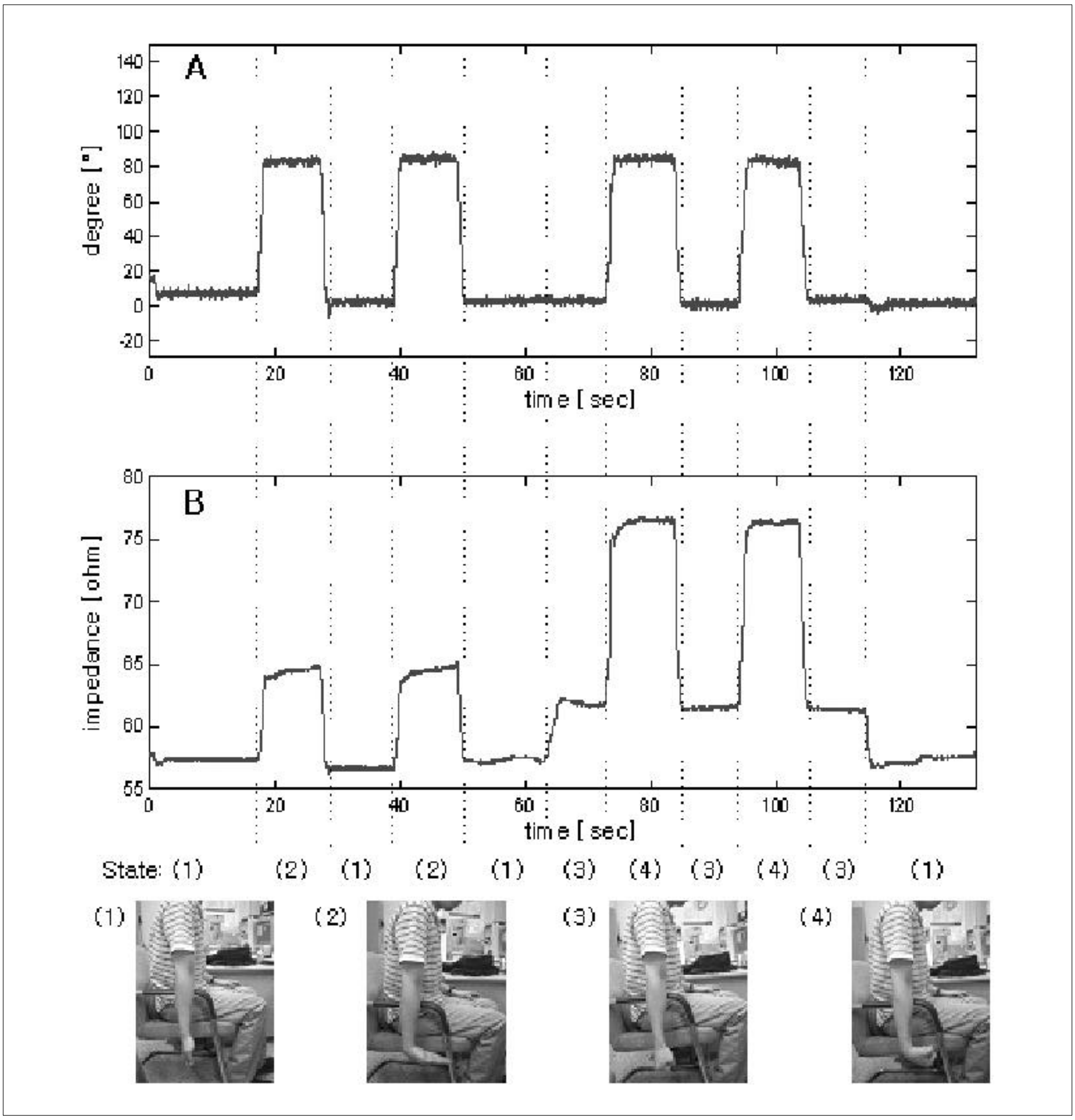


Fig. 4. Wrist angle changes (A) and impedance changes (B) during wrist extensions and flexions with finger extensions or flexions.

wrist moved from extension (state 1) to flexion (state 2), whereas impedance decreased when the wrist moved from flexion to extension.

When the fingers were flexed, both impedances for wrist extension (state 3) and flexion (state 4) increased compared to both cases with finger extension (states 1 and 2), because finger flexion resulted in muscle contraction and thus increased muscle impedance measured in Ch1 in Fig. 2. Based on the above observation, it can be concluded that wrist extension and flexion can be measured with fingers in states of extension or flexion using the bio-impedance technique.

Elbow movement

Fig. 5 shows a change of elbow joint angle (A) and the corresponding impedance change on the upper arm (B). The impedance change was measured between the electrode pair on the upper arm from Ch 2 in Fig. 2. When the elbow was flexed while the wrist and fingers were extended

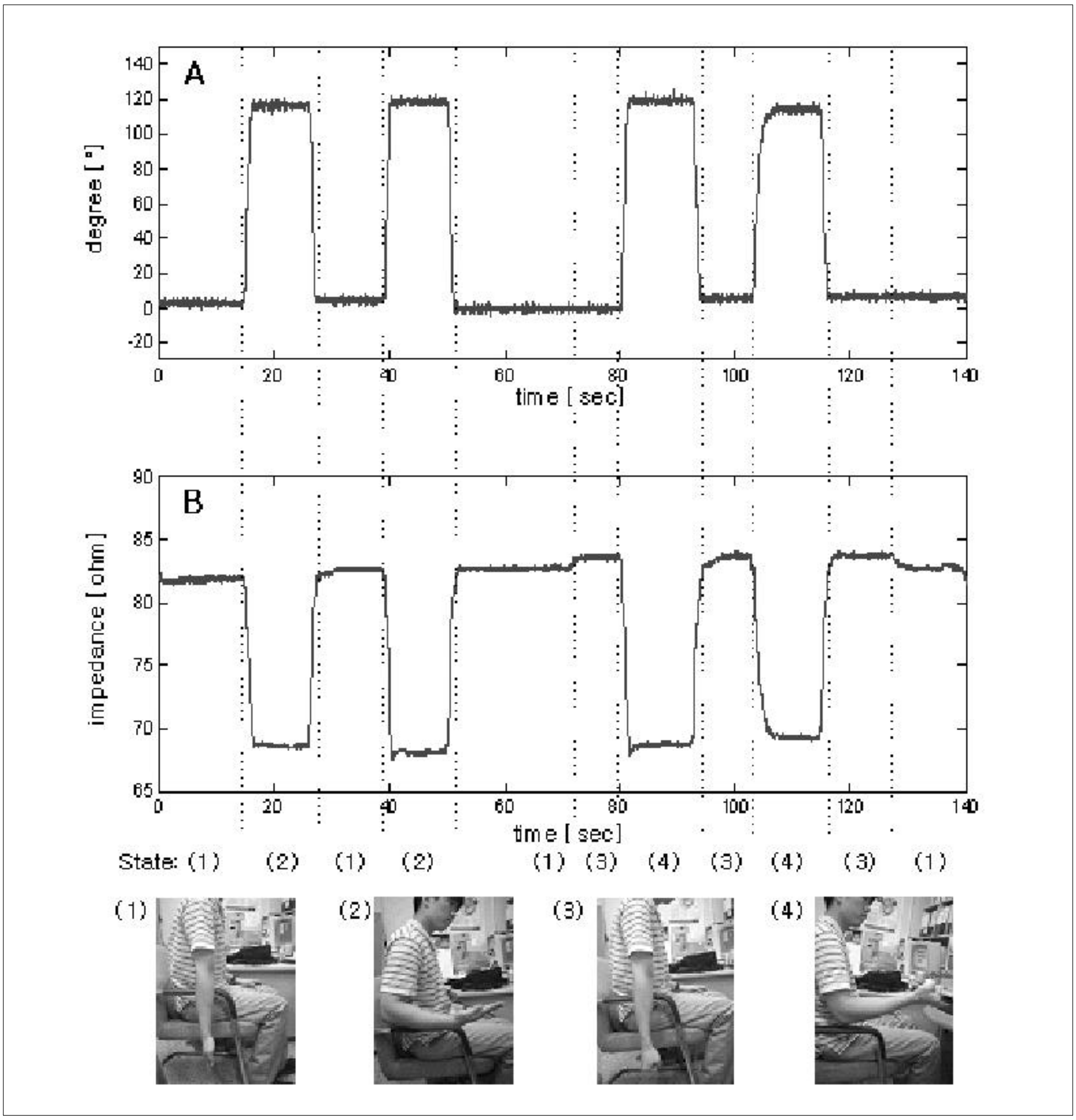


Fig. 5. Elbow angle changes (A) and impedance changes (B) for elbow extensions and flexions with finger extensions or flexions.

(state 2), the impedance decreased compared to the elbow extension (state 1). This decrease was due to the increased muscular volume of the upper arm under the voltage electrode pair. On the contrary, impedance increased when the wrist moved from extension to flexion. The impedances of elbow extension (state 3) and flexion (state 4) with finger flexion were approximately the same as those with finger extension as shown in Fig. 5(B). This means that the state of finger extension or flexion does not affect the impedance of upper arm.

Correlations between angles and impedances

Figs. 6 (A) and (B) show the relationships between the wrist joint angle and impedance changes of the forearm (r=0.98) and between the elbow joint angle and impedance changes of the upper arm (r=-0.99), respectively. The data in Figs. 6 (A) and (B) were obtained by repeating extension and flexion of a subject's wrist and elbow 20 times, respectively. The average correlation coefficients for the wrist and elbow movements of 12 subjects were 0.96 ± 0.04 and -0.98 ± 0.02, respectively.

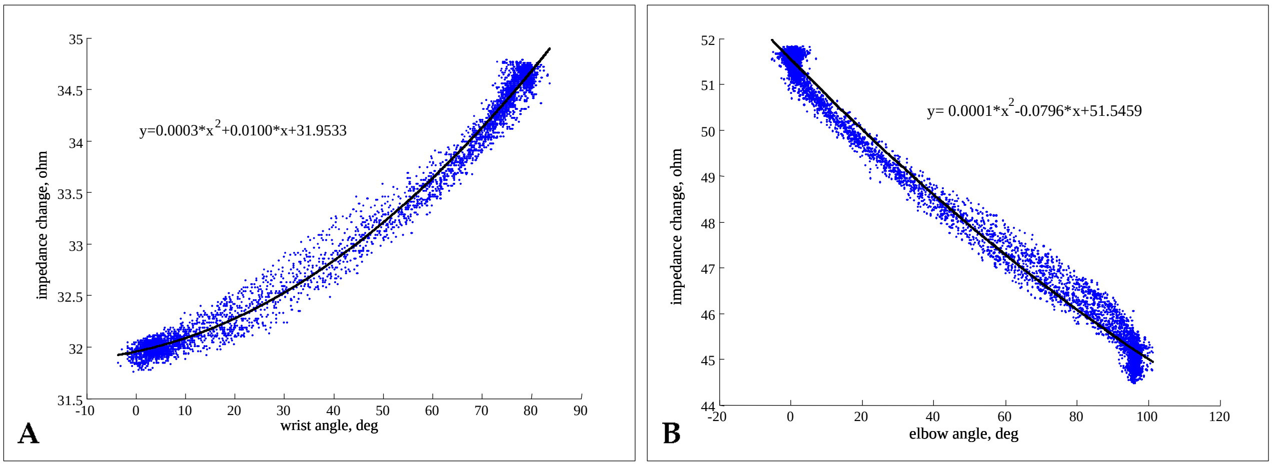


Fig. 6. Relationships between impedances and the wrist angles (A) and between impedances and elbow angles (B) for a subject.

Reproducibility

To evaluate reproducibility, the impedance differences between extension and flexion of the wrist and elbow were obtained by investigating five repetitions per subject. The average impedance differences of extension and flexion of the wrist and elbow were 3.4 ± 1.5 ohm, and 9.9 ± 4.6 ohm, respectively for 12 subjects. Reproducibility was evaluated using Eq. (2) by performing five repeated measurements on each subject. The average reproducibilities of the wrist and the elbow movements for the 12 subjects were 2.1 ± 1.0% and 1.8 ± 1.0%, respectively.

$$\text{Reproducibility} = \frac{\text{standard deviation}}{\text{mean}} \times 100[\%] \qquad (2)$$

DISCUSSION

In this study, a method of estimating upper limb movement by measuring bio-impedance is proposed. The study shows that wrist and elbow movements can be determined from impedance measurements of the forearm and upper arm, respectively. In both cases, very high correlation coefficients between impedance and joint angle were obtained. Impedance is proportional to the length of the measured regions, and inversely proportional to the cross-sectional area. Thus, it was confirmed that movement of a joint leads to the contraction or relaxation of a muscle, and results in a change in the cross sectional area of the muscle. While the measured impedance may be different in different individuals, the reproducibility for each subject was excellent.

Both the flexor carpi radialis and palmaris longus muscles participate in wrist movement. It is believed that the increased impedance of the forearm when the wrist or fingers are flexed is caused by a decrease in the cross sectional area of muscle under the voltage-sensing electrodes. For elbow movement, the biceps brachii muscle participates in extension and flexion, and it is clear that when the elbow moves from extension to flexion, the cross-sectional area of the biceps brachii muscle increases, thus decreasing the impedance. However, for more complex movements, such as supination, pronation, and rotational movements, muscle cross-sectional area and distortion occur simultaneously. Therefore, additional channels and corresponding electrodes would be required to analyze these more complex movements.

The present study demonstrates that it is possible to accurately measure upper limb movements without limiting the movement of the upper limb, as for example, compared to a goniometer, by using surface electrodes attached on the skin. Moreover, as long as the positioning of electrodes is consistant, the reproducibility and correlation of the impedance method are excellent, and thus it can be used objectively to analyze upper limb movement. On the other hand, this method has a few disadvantages, for example, it cannot measure multi-joint movements and it requires calibration to measure accurate joint angles in each subject. However, it has several advantages over the video analyzer, because it is simple and less expensive, and requires very little space. Bio-impedance method also has advantages as compared to EMG, as fewer calculations are needed and it has an intrinsically high signal to noise ratio. If wireless technology were applied to this method, it would have wide-ranging possibilities in sports applications, which require large spatial movements and continuous measurements over extended periods. In addition, if this bio-impedance method were applied to measure lower limb movements, it might be useful for gait analysis or to evaluate the effectiveness of new therapies.

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