USING ELECTROMYOGRAPHY OF FIVE MUSCLES AND JOINT ANGLE TO PREDICT KNEE JOINT MOMENT

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Forces and moments acting on joints is of great importance in different fields of biomechanics such as ergonomics, sports biomechanics, and rehabilitation. EMG-driven models can be used to estimate forces and moments acting on joints. The current study aimed to propose a model for prediction of knee joint moment using EMG signals detected from muscles and knee joint angle. Electromyography of knee muscles, knee joint angle and moment were recorded simultaneously during the extension-flexion movement in three young men using an isokinetic system. The model for estimating knee joint moment was developed using multiple linear regression. In order to calibrate and validate the model, new data was entered into the model and the estimated moment was compared with the measured moment. The model estimated knee joint moment with an acceptable accuracy, so that coefficient of determination (R^2) was between 0.9 and 0.95.

KEYWORDS: Knee moment, EMG driven model, Linear envelope.

INTRODUCTION: Measuring the forces and moments acting on joints and estimating the contribution of each muscle to these forces is a basis to understand the functions of joints. The joint moment prediction is also essential to determine the standards of movements in daily work conditions, exercises and rehabilitation movements. Since it is not possible to directly measure these factors, modeling is usually used to estimate them (Reeves, 2003).
Surface electromyography (sEMG) has been used as an indirect and non-invasive method to predict joint forces and moments. In these models, various techniques such as regression (Sun et al., 2013; White et al., 1992), optimization (Amarantini et al., 2010; Chung et al., 1999), Hill-based model (Lloyd, 2003; Langenderfer et al, 2005; Shao, 2009) and neural networks (Luh et al., 1999) have been applied to estimate forces and moments acting on the joints.
Regression has been used to develop an EMG-driven model to predict moments acting on the joints (Sun et al., 2013; White et al., 1992). In order to estimate moments using regression model, EMG and biomechanical data such as joint angles, joint angular velocities and moments were collected. Then, the moment estimation model was obtained using sEMG and other measurable biomechanical factors. High simplicity, lack of complexity, and acceptable reliability and accuracy compared to other models are some advantages of the regression model. Unlike the Hill based model, this model does not require muscle parameters such as muscle length (Lloyd, 2003; Langenderfer et al, 2005; Shao, 2009). On the other hand, complicated mathematical calculation in the optimization models is not required (Amarantini et al., 2010; Chung et al., 1999).
Since it is very important to validate these models, lack of validation or the use of computational methods for validation can be the other weakness of the previous studies. The main aim of the present study was to develop a model for estimating moment acting on the knee joint based on electromyography of five muscles of the lower extremity.

METHODS:

Data Collection: Three healthy adult men with an average age of 26.6 ± 0.9 years, average height of 165.1 ± 8.1 cm and average weight of 69.3 ± 6.6 kg, were randomly selected among the volunteer students of Sahand University of Technology. They had not experienced musculoskeletal disorders, and back or lower extremity surgery. Oral and practical explanation of the data processing procedure was presented to all participants. All participants read research information sheets and gave written consent to participate in the

test. The study was approved by the Graduate Committee of Sahand University of Technology and the Ethics Committee of Tabriz University of Medical Sciences.
Participants attended the biomechanical laboratory of the Physical Medicine Center of Imam Reza Hospital in Tabriz, where they got changed and wore the clothes prepare for the test. Prior to electrode placement, the skin surface was shaved (if needed), rubbed by a soft towel and cleaned by alcohol swab to reduce skin impedance (<20 K_). Ag / AgCl surface electrodes were placed on the prepared locations on rectus femoris, vastus medialis, vastus lateralis, hamstring and gastrocnemius muscles, following the recommendations of De Luca. A ground electrode was also placed on the epicondyle of the tibia. Then, cables were fixed using surgical adhesive to prevent movement of the cables, collisions between them, and noise.
Biodex System 4 Pro™ isokinetic device with 100 Hz sampling rate was used to measure the knee moments. Each participant sat on the seat of the isokinetic device, and then the belts were tightened to prevent unwanted movements and to limit hip motions. Then the participant's dominant leg was tightened to the device using belts. The seat height, spacing and lateral condyle of the tibia were adjusted to the device rotation axis. A movement protocol was defined for the isokinetic software so that the knee concentric-concentric flexion-extension was controlled with constant angular velocity of 60 degrees per second. Simultaneously with isokinetic data collection, the EMG data of the 5 muscles were recorded using an 8-channel biometrics device (Biometrics Data Log p3x8) at 1000 Hz sampling rate. All records were repeated five times with 2 minutes interval between trials After a half an hour, sampling was repeated for five times to obtain data for model validation.
Electromyography signal processing: Data processing was performed using Bio Proc2 software which is professional software for analyzing electromyography and biomechanical data. A fourth-order zero-lag Butterworth high-pass filter with a frequency of 10 Hz was used to remove movement-related noises. Signal smoothing was performed after full rectification and applying a band-pass filter of 10 to 500 Hz using the moving average method with a window size of 0.05 seconds. Then, linear envelop of the signals was calculated by the software. All resulting data were normalized to the maximum value of signal amplitude during the corresponded movement.
Modeling: The relationship between model coefficients, independent and dependent variables is as follows:

$$T = a_0 + a_1 X_1 + a_2 X_2 + \cdots + a_i X_i \qquad (1)$$

Where, a_i is the multiple linear regression coefficients and a0 is the constant term. In the present study, independent variables, Xi, were the normalized electromyography signals of rectus femoris, vastus medialis, vastus lateralis, hamstring and gastrocnemius muscles, and joint angles of participants and the dependent variable, T, was the measured moment. Coefficients of the model were calculated by using SPSS software.
Model Validation: At this stage, electromyography of the muscles and also the angle of knee (different from the modeling data) were used as the input data for calculating the knee moment by the obtained model. The knee joint moment was calculated for each participant in all three repeats. Then, the average of the calculated moments for the participants was determined as the moment for validation.
The estimated moment by the developed model and the measured moment by the isokinetic device were entered into MATLAB. The curve fitting method in MATLAB Software was used to validate the estimated moment. Then the first-order polynomial was selected as the fitting method and the curve fitting was measured. Model validation was performed using this method, and the coefficient of determination (R^2) was estimated for the moment curve fitting.

RESULTS: Table 1 shows coefficients and standard deviations of the regression model. The coefficients of the model driven from EMG show significant contribution of the EMG signals of vastus medialis, rectus femoris, vastus lateralis, and gastrocnemius muscles and also joint angle in the moment estimation ($P < 0.001$). The model constants were also significant at the confidence level of 0.95. According to the coefficients and multiple linear regression, the following moment (T) estimation model was obtained:

$T=-5.91+1.75X_1+0.37X_2 - 0.74X_3 -0.79X_5 - 0.09X_6$

Where, T is moment (torque), Xi is independent variable (EMG of the muscles and joint angles).

Table 1: Coefficients of the EMG driven model

Independent variables	Xi	Coefficient	Standard deviation	P value
Constant	-	-5.91	2.15	0.007
EMG of vastus medialis	X_1	1.75	0.11	0.001
EMG rectus femoris	X_2	0.37	0.10	0.001
EMG of vastus lateralis	X_3	-0.74	0.10	0.001
EMG of hamstring	X_4	0.17	0.12	0.158
EMG of gastrocnemius	X_5	0.79	0.11	0.001
Knee joint angle	X_6	0.09	0.02	0.001

To validate the above model, knee joint moment was estimated by entering new EMG data (validation data) into the model (R^2=0.95) and the output is shown in the figure 1.

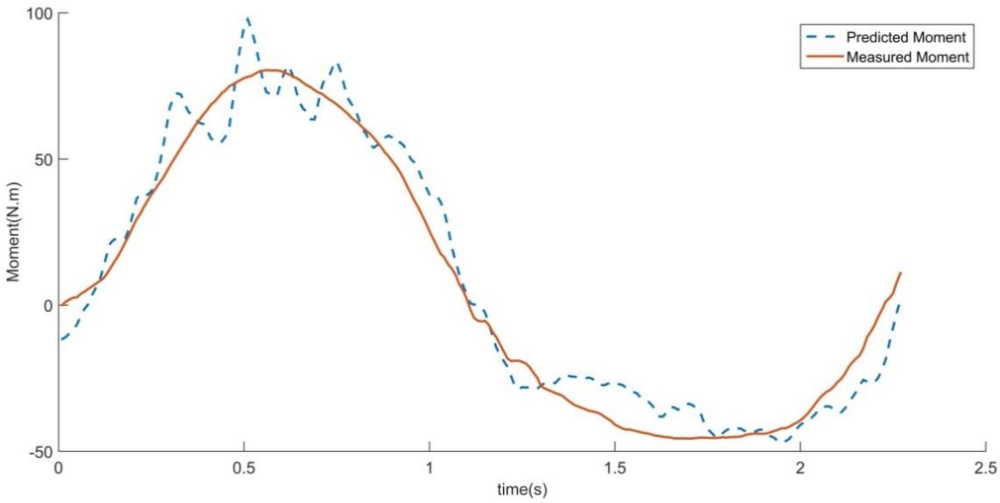

Figure 1: The moments measured and estimated by the EMG linear envelope driven model

DISCUSSION: The present study aimed to propose an EMG-driven regression model for estimating knee joint moment. The model was developed and validated using linear envelope of electromyography signals of five muscles of the lower extremity as well as the knee angle. The result of the study showed high correlation between the estimated knee moment by the developed model and measured moment.

In the present study, maximum error (standard deviation of mean) of model coefficients was 12%. In another study, Sun et al. (2013) used EMG of two muscles to develop their model. They reported maximum errors of 25% and 21% for the optimized model in knee extension and flexion respectively. This implies that in the regression model, increasing the number of muscles can be considered as an effective factor in improving the model accuracy. However, they studied one participant while in the present study the data of three participants were

used in the model development. In the present study, coefficients of determination (R^2) of the model showed higher correlation (> 0.79) which was reported by White et al. (1992). This implies that the present study estimated effects of the components more accurately.
In the present study, EMG of muscles as well as joint angle were used to estimate the knee moment. The joint angle changes the moment arm and consequently changes moment acting on the joint. The developed model in the current study showed that the joint angle has significant effect in the model which is in agreement with the theory.
Data collection during a single session could be considered as a limitation of this study. Previous studies showed that the reliability of EMG signals recorded during in a session is different from those recorded during several sessions (Oskouei et al., 2013). It is recommended to collect data in different sessions for model developing and its validation. The study didn't look at the reliability of the data which could be another limitation. The data were also collected during the knee flexion while the angular velocity was constant. This could limit the practical application of the study to the movements with constant angular velocities such as exercises for patients after a surgery. That is recommended to develop the model in different angular velocities.

CONCLUSION: The present study indicated that a regression model surface EMG of the lower extremity muscles together with knee joint angle can be used to estimate knee joint moment. According to the results, the model driven from EMG liner envelope of rectus femoris, vastus medialis, vastus lateralis, hamstring and gastrocnemius muscles were suitable for estimating the knee joint moment. The best result was obtained when linear EMG envelope in the five muscles was used together with knee joint angle in the regression model.

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