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Study of Human Upper Arm Girth during Elbow Isokinetic Contractions Based on a Smart Circumferential Measuring System

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***Abstract*—**As one of the convenient and noninvasive sensing approaches, the automatic limb girth measurement has been applied to detect intention behind human motion from muscle deformation. The sensing validity has been elaborated by preliminary researches but still need more fundamental studies, especially on kinetic contraction modes. Based on the novel fabric strain sensors, a soft and smart limb girth measurement system was developed by the authors' group, which can measure the limb girth in-motion. Experiments were carried out on elbow isometric flexion and elbow isokinetic flexion (biceps' isokinetic contractions) of 90°/s, 60°/s, and 120°/s for 10 subjects (2 canoeists and 8 ordinary people). After removal of natural circumferential increments due to elbow position, the joint torque is found not uniformly sensitive to the limb circumferential strains, but declining as elbow joint angle rises, regardless of the angular speed. Moreover, the maximum joint torque was found as an exponential function of the joint's angular speed. This research highly contributes to the application of the automatic limb girth measuring during kinetic contractions, and it is useful to predict the contraction level of voluntary skeletal muscles.

***Keywords*—**Fabric strain sensor, muscle deformation, isokinetic contraction, joint torque, limb girth strain.

I. Introduction

As the motor of sports, the skeletal muscles are one of key issues that have been arousing scholars' interests. The design of specific training should be informed or advised by biomechanical analysis of the movement and the study of the athletes, and by some important index of muscles' contraction status, such as torque or electromyography (EMG) [1], [2], urging improvement of technology elements in all aspects, e.g., facilities, training methods and monitoring equipment. There is an increasingly demand for real-time monitoring of human physiological and mechanical signals, which are necessary to quantify the training process and evaluate the training effect [3], [4]. The trial use and applications of intelligent monitoring systems have been conducted for professional athletes. Observations were presented not only on the physical properties but also the working mechanism.

Modern science and technology has been boosting the training schemes in most details, i.e. muscle coordination, contractile force, fatigue, and muscle activation. Take weightlifting for an example, classic studies have been predominantly concerned with the analysis of trajectory of a barbell and angular dynamics data of the body [5] in a sagittal plane. In nowadays, however, coaches have strong needs to know a lot more that could provide advices to help athletes do better. Among these that have been carried out, most attention is focused on macroscopic aspects such as kinetic analysis of the athletes, and on microscopic aspects such as biomechanical properties of a single muscle or muscle group [6] and muscle motion due to activation, and activation-force-motion models have been established and updated to create links between them [3], [4], [7].

To build a time variable muscle monitoring system, since direct measurement of muscle forces is generally not feasible in clinic, non-invasive methods should be considered, on force output and also on contraction levels. Since torque output is also affected by joint position and muscle shortening speed (due to the operation mechanism of muscle fibers), experiments are done on Isometric contractions and kinetic contractions, or both. [2], [8], [9] Surface electromyography (sEMG, or EMG) is a well-known noninvasive method to measure the activation level of superficial skeletal muscles, however, it is often influenced by several external factors altering its shape and characteristics, that is, tissue characteristics, physiological cross talk, changes in the geometry between muscle belly and electrode site, external noise and electrode and amplifiers [1]. Most importantly, it is time-consuming to have the EMG signals processed. Although there are some other approaches to detect muscle contraction states, such as sonomyography (SMG) and mechanomyography (MMG), but they are also not appropriate for convenient use in training. Up-to-date, very few equipment have been successfully devised for portable training practice.

In recent years, novel sensors and fabrication technologies on human ergonomics in related projects and studies [10]-[12] have been boosting the research on muscular bio-mechanics. Based on a fabric tensile/ compressive sensor array [11]-[14], which is soft, light, and with good stability and repeatability, a smart sensing belt is developed, which is portable, comfortable and suitable for real time monitoring in sports training. Based on these works, a limb gauge measuring system was designed, which can measure the girth's change of limbs during human movements, and as such could improve weightlifting (or other sports) training technologies. The measuring system is light and portable, suitable not only for research in lab and clinic, but also for professional sport activity monitoring.

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II. METHODOLOGY

A. Measuring System

The measuring system is designed to continuously measure the circumferences of limbs during movements. It consists of three parts, i.e., fabric strain sensors, data acquisition module (DAQ), and program interface, where the fabric strain sensors are soft, portable, supporting large deformation as 60% and easy to use (Table I).

TABLE I
PERFORMANCE SPECIFICATIONS OF FABRIC SENSOR ELEMENTS

Performance	Sensor element
Strain measurement range	0-60%
Linearity	±5%
Repeatability	±5%
Hysteresis	±5%
Gauge factor	1-100
Working temperature	0-60℃
Fatigue resistance	>100,000 cycles
Temperature compensation range	0-60℃
Relaxation	±5%/30min
Zero-drift with time	±5%/h

1. Calibration of Measuring System

Before measurement, the fabric strain sensors were calibrated by a designed calibration device (Fig. 1). Fixed on the shafts, it was stretched to 5% strain and then 15% strain to obtain the sensitivity. After calibration, the measuring system is mounted on the location of maximum circumference of one subject's upper arm with flexed elbow. Measurement is conducted and transferred by DAQ to the computer and shown on the program interface. The sampling frequency is 30~60 Hz, and its battery (integrated in DAQ) can serve for 5 hours' service, which is sufficient for training use. The measuring system for human upper arm covers a measuring range of 25cm~40cm, and with a circumference measuring accuracy of ±5%.

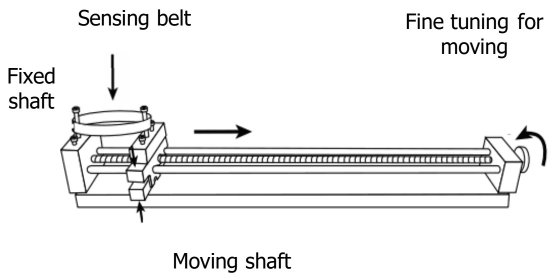

Fig. 1 Calibration device of the measuring system

After calibration, the sensing belt is mounted on the location of max girth of one subject's upper arm with flexed elbow, as shown in Fig. 2.

B. Effect of Joint Position on MVC

Contractile force of elbow flexors can be measured directly by joint torque (torque), which is the cross-product of contractile force of muscle and moment arm of skeletal muscle to the joint. Joint positions affect not only the maximum contractile force of skeletal muscles as a result of different muscle fiber lengths for different positions, but also moment arm. Firstly, length and moment arm of some human skeletal muscles have been studied, revealing an obvious effect of joint position. Fig. 3 gives a schematic view of how the elbow position affects the muscle length of the flexors, influencing the force output.

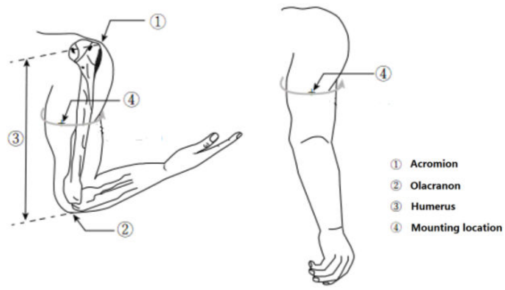

Fig. 2 Mounting location of the sensing belt on human upper arm

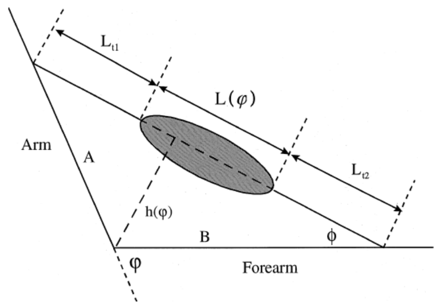

Fig. 3 Schematic view: elbow position and the muscle length

During isometric contractions, MVC torque does not stay at a same level, but changes for different positions. As has been presented many times, the maximum torque depends on the joint positions [2], [15]. The position effect on the maximum torque should thus be studied first.

Isokinetic contractions and isometric contraction will both be conducted. For isometric contraction, subjects try isometric contraction at different positions, and the max torque will be recorded. For kinetic contractions however, take example the elbow flexion, when position changes, the shortening of muscle leads to an increase of the thickness, which is not totally caused by contraction. Limb girth strain and torque of subjects are measured or calculated for different positions, yielding a continuous curve of the measuring sensitivity to different positions. Previous work [9] considered this issue and extracted the overall limb girth during contraction with natural girth to current position, as in (1), which reveals that the measuring sensitivity u is different for different positions. Basically, the cross-sectional deformation of skeletal muscle during contraction depends on the deformation of sarcomeres which is related to joint position, and the number of sarcomeres involved during contraction. How much the girth would change to generate certain amount of torque is a summation of these two issues, which cannot be easily explained by the effect of Poisson's ratio. Since it would be complex to build a model to fundamentally describe the length effect (or effect of joint position), experimental identification of the measuring sensitivity is an alternative approach.

$$u = \frac{g(\theta) - g_{nature}(\theta)}{g_{nature}(\theta)} \tag{1}$$

For isometric contractions, similarly, measuring sensitivity is calculated for different fixed positions and the sensitivity curve can be obtained through curve-fitting. For same subjects, the curve could be compared with the continuous sensitivity curve obtained from kinetic contractions. For isokinetic tests for human elbow, Biodex® should be adjusted to fit the subjects first. Subjects try flexions and extensions freely without loading. Then three angular speeds were selected, 90°/s, 60°/s and 120°/s. For each speed, two sets of 3 cycles of flexion-extension were performed by subjects, with about 1min between two sets for rest.

Real-time torque was collected during the whole course. The limb girth strain, as given in (1), was calculated. $g(\theta)$ is the limb girth measured in kinetic contraction (flexion), while $g_{nature}(\theta)$ is the natural limb girth to different joint positions, also the limb girth measured in freely tries(relaxed). Based on the torque and limb girth strain to different positions, the sensitivity can be given as:

$$f_\theta = \frac{T/MVC}{s} \tag{2}$$

where T is the joint torque, and s is the limb girth strain.

C.Effect of Angular Velocity (Shortening Speed) on Torque

Since the contractile ability is affected by the shortening speed, also the angular velocity of the joint if we are focusing on movement of joint, for isokinetic contraction of different angular velocity, the max torque can be recorded. The maximum torque normalized by MVC is the effect of the angular velocity during kinetic, named the f_ω. Isometric is an extreme case of 0°/s. The discrete angular velocity- f_ω could be interpolated through curve-fitting techniques.

III.Results

A.Limb Girth Strain and Circumferential Measuring Sensitivity to Positions

In this part, isokinetic data of 10 subjects would be analyzed. The isokinetic analysis of subject 6 is presented to illustrate the typical procedures of analysis of isokinetic contractions. The typical strain detected by sensors and overall girth is illustrated in Fig. 4.

To have the measuring sensitivity to different joint positions, torque of flexion is first extracted, as in Fig. 5.

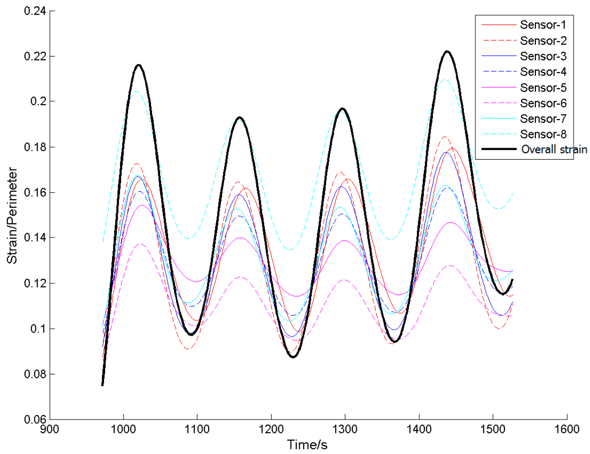

Fig. 4 Typical original data, strains and overall strain

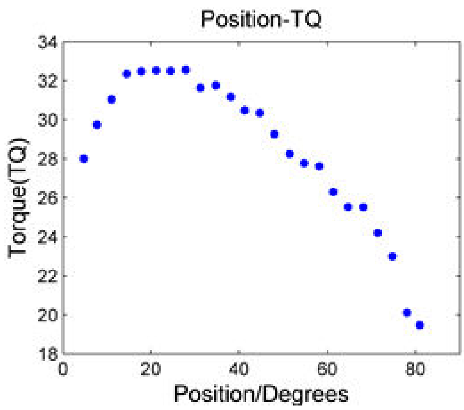

Fig. 5 Typical torque-position curve during flexion of isokinetic contraction

The LC during free trail (without load/resistance) and during isokinetic flexion and limb girth strain calculated are in Fig. 6.

Using (2), a typical curve (from subject 6) of the sensitivity to position is shown in Fig. 4.

One thing that should be mentioned is that, the sensitivity of f_θ to joint position obtained from isokinetic contraction is similar from that obtained from isometric contraction at different positions, as shown in Fig. 8. However, variations are found between calculations using different flexion phases, as shown in Fig. 9. The reason is to be discussed. Similar phenomenon can be found with other subjects.

B.Maximum Torque during Isokinetic Decreases as Angular Velocity Increases

As elaborated, for isokinetic contraction of different angular velocity, the maximum torque can be recorded. The maximum torque normalized by MVC yields the effect of the angular velocity during kinetic, named the effect of angular velocity.

Maximum torque for four angular speeds are found: 0°/s, 90°/s, 60°/s and 120°/s. The maximum torque is normalized by MVC at 0°/s, and shown in Fig. 10.

A clear exponential relationship can be found between contraction speed and its influencing coefficient. This conclusion could be further consolidated by data from the other four subjects.

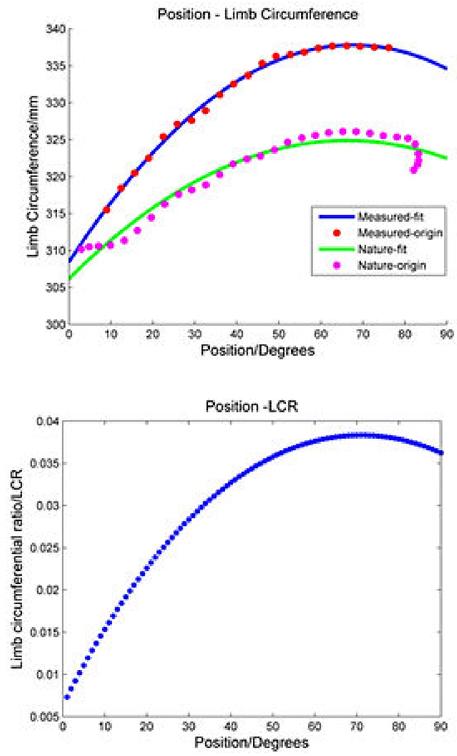

Fig. 6 LC and limb girth strain during flexion of isokinetic

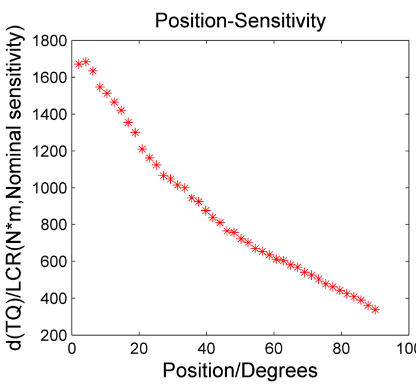

Fig. 7 Measuring sensitivity (f_θ) to joint positions

IV. Conclusion

The measuring sensitivity to position is another representation of the muscle length effect on the contractile force production. One apparent conclusion could be drawn that the larger the position angle, the less the sensitivity. Detailed procedures and results have been elaborated above, along with the influencing coefficients of contractile speed, which can be fitted from Isometric MVC and Isokinetic maximum torque. The results of measuring sensitivities show that limb girth ratio (limb girth strain) is not an all-position index for skeletal muscle contraction. Moreover, contraction ability is different at different joint angular speeds (the maximum joint torque was found as an exponential declining function of the joint's angular speed), resulting in a different efficiency of muscle contraction. This effect can also be obtained by MEASURING SYSTEM in Isokinetic contractions of different speed. These results could highly contribute the application of limb girth as a prediction of contractions of skeletal muscles.

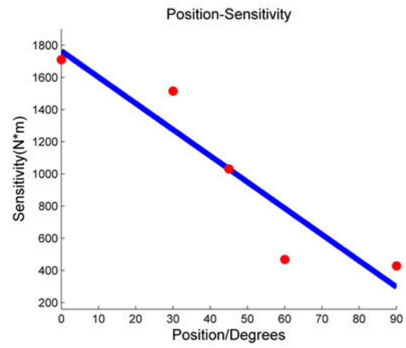

Fig. 8 Sensitivity obtained from isometric contractions, blue line is the curve-fitted line using experiment data

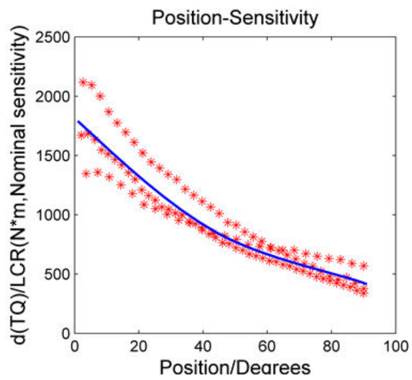

Fig. 9 Variation between different calculations using different flexion phases

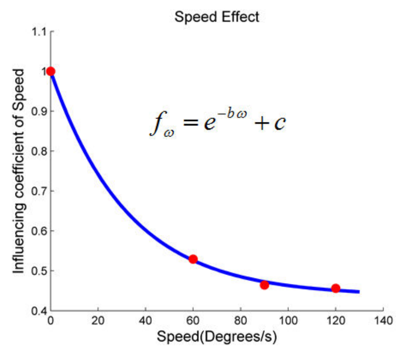

Fig. 10 Effect of angular speed on the maximum torque during isokinetic contraction

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