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Wearable Monitoring and Predicting System for Knee Joint Fatigue Based on Curvature and Pressure Sensing

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Abstract

Background: Knee injury is always a trouble for people in daily life. It not only threatens the career of an athlete but also affects a normal engineer through morning running. The injury of the knee joint is found to be directly related to the fatigue caused by excessive exercise.

Methods: An economical embedded system with a designed acceleration-weighted curve fitting method was developed to estimate and predict the knee fatigue state. Then the warning message and recommended lasting time were sent to users to avoid excessive exercise. 24 healthy volunteers were involved in the experiments to verify the effectiveness of the system compared to human perception.

Results: Only using human perception to prevent knee joint fatigue had a risk of failure while the designed wearable system could protect knee successfully. It was also found that

the knee of female was more likely to be injured than the one of male in intense exercises and a high BMI value could influence the risk of knee injuries during sports. However, a short break in sports could significantly extend the healthy time for knee.

Conclusions: Early warning from the specially designed embedded system can successfully help people avoid knee joint fatigue and injuries during exercises, such as running, badminton, table tennis and basketball.

Keywords: knee joint; fatigue; wearable device; exercise; health

1. Background

Knee joint injuries often occur during exercise and cause more than four weeks absence from jobs or team-sports competitions. The anterior cruciate ligament (ACL) lesions and meniscal and medial collateral ligament (MCL) sprains are most common knee joint injuries in daily life. The rate of ACL lesions even reaches 2.8 and 3.2 injury per 10,000 h of exposure in basketball and soccer players from university, respectively [1]. Moreover, ACL rupture usually needs surgical reconstruction and a recovery period over six months which may bring a shadow to the career of an athlete or normal work of an engineer [2]. People's daily strenuous physical exercise without restriction may also cause acute or chronic injury to the knee joint, resulting in body and economic losses. Therefore, prevention of that injury in sports is an important and meaningful work in sports protection. The studies have found that knee injury from sports is closely related to knee joint fatigue caused by excessive exercise [3-5]. Thus, if the knee joint fatigue can be estimated and predicted during the sports, early warning can be made to reduce the intensity or duration of the exercise.

Previous researches have focused on the monitoring of knee joint motion [6]. A wearable goniometer and accelerometer sensory prototype with a Kalman filter for data fusion has been made to measure the flexion-extension angle of knee [7]. In evaluation, the prototype is able to acquire reliable data in dynamic knee movements, but it has not provided an economical embedded solution of portable device for daily application and is without the testing dataset on real sports of human. Another motion capture system based on 17 inertial units and 53 opto-reflective markers is proposed to measure

the knee adduction and joint contact force during daily living activities of elderly people with knee osteoarthritis [8]. This research proves the feasibility of the inertial motion detecting system but lacks the data analysis for actual daily applications. Furthermore, amounts of sensors applied in the system increase the cost and structural complexity of it, and may make it hard to be adopted widely in daily life. In order to improve the detecting accuracy and portability of the devices, the new structural sensor made by ordinary fabrics and conductive yarns [9] and mobile communication technique [10] are also involved in. The ground reaction forces of ski jump landing related to knee are studied using wearable sensors [11]. In that study, the plantar force insoles are combined with inertial motion units to determine the possible relationship of those forces. However, none of these studies linked the movement and stress of the knee joint to the fatigue judgment of knee, which is the key to knee protection.

In order to keep health of knee in sport competition and daily exercise, sensing equipment and an estimated system are built in this paper to help people control their exercise intensity and duration. The primary contributions of this report can be described as follows: (1) link the knee injuries to its fatigue and propose a comprehensive load formula for knee joint fatigue estimation; (2) the acceleration of the end of the tibial which reflects the active intensity of the muscles around the knee joint is measured as an additional weight for curve fitting and a proportional-integral controller is also involved to increase the predicting accuracy; and (3) an economical sensing system based on ST Microelectronics (Geneva, Switzerland) STM32F103 platform is developed to validate the effect of the algorithm and be a prototype for daily use. The remainder of this report is organized as follows: after reviewing related knee joint physiology in Section 2, we provide a fatigue judgement algorithm for knee joint in Section 3. In Section 4, a real-time embedded hardware is built to sense the load of knee joint during exercise. The experimental results are presented in Section 5. Finally, the conclusions are stated in Section 6.

2. Results

Figure 1 shows the flexion angle and plantar pressure data during running and playing basketball acquired by the devices and presents the illustration of cubic polynomial fitting estimation for knee

78 fatigue. It can be found that the degree of knee fatigue increased with time during the exercises and the
79 designed system is successful to estimate the fatigue of knee joint in real time. Figure 2(a) shows the
80 healthy time of different genders for knee joint during the four exercises without break which can keep
81 the fatigue degree of knee less than 80 present. It is obvious that the knee of female is more likely to be
82 injured during these exercises and the tendency is more significant in sports like basketball and
83 running in which the movements are more intense in the lower limb. Figure 2(b) shows the healthy
84 time of different BMI situation during the exercises without break. When playing badminton and table
85 tennis, the participants with BMI value less than 24 are able to have more time to stay healthy for knee
86 joint. The difference is not significant in playing basketball and running although their mean values
87 have the same tendency. This may be due to the large time variance caused by the deviation of people's
88 personal tolerance to playing basketball and running. Thus, the people with larger BMI value may have
89 higher risk of knee injuries during playing badminton and table tennis. This may be due to the fact that
90 excessive body weight puts more loads on the leg muscles during exercise. As shown in Figure 2(c),
91 the short break during sports can significantly extend the healthy time for these exercises and avoid
92 knee injuries efficiently; conversely, long-term high-intensity continuous exercise will increase the risk
93 of knee injury. After 14 days of first stage testing, none of the participants reported discomfort or pain
94 in their knee joint.

95 In the second stage of experiment, the testing group equipped the sensing device for warning
96 fatigue of knee joint while the control group depended on the feeling of themselves. As shown in
97 Figure 3(a) and (b), the Lysholm scores and IKDC scores of control group were significantly
98 decreased after running and playing basketball while the ones of testing group did not changed
99 obviously. This proved that only using human perception to prevent fatigue of knee joint and avoid
100 injury had a risk of failure; and the use of a suitable electronic predicting system could achieve this
101 goal. Because playing basketball is more intense than running for knee joint, the reduction in scale
102 scores is more significant, and the changes in Figure 3(a) and (b) conformed to this trend. Figure 3(c)
103 and (d) shows the Lysholm sores and IKDC scores of control group for different genders before and
104 after playing basketball and running. It can be found that female suffered more decrement in scale

sores than male during these two sports, which implied that women is more dangerous to be injured in knee than man in these sports. This trend is consistent with the conclusion in the first stage of experiment. Figure 3 (e) and (f) also shows that the BMI value could influence the risk of knee injuries during sports.

Figure 1. (a) Illustration of flexion angle data acquired by the device in running; (b) Illustration of plantar pressure data acquired by the device in running; (c) Illustration of predicting curve of knee fatigue in the 38th minute for running; (d) Illustration of flexion angle data acquired by the device in playing basketball; (e) Illustration of plantar pressure data

acquired by the device in playing basketball; (f) Illustration of predicting curve of knee fatigue in the 24th minute for playing basketball.

Figure 2. (a) The healthy time of different genders for knee joint during the four exercises without break; (b) The healthy time of different BMI situation for knee joint during the four exercises without break; (c) The healthy time for knee joint during the four exercises with and without break. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

Figure 3. (a) Lysholm sores of testing and control groups before and after playing basketball and running; (b) IKDC sores of testing and control groups before and after playing basketball and running; (c) Lysholm sores of control group for different genders before and after playing basketball and running; (d) IKDC sores of control group for different genders before and after playing basketball and running; (e) Lysholm sores of control group for different BMI situation before and after playing basketball and running; (f) IKDC sores of control group for different

BMI situation before and after playing basketball and running. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

3. Discussion

According to the experimental results, the designed estimation and predicting algorithm has ability to warn the risk of knee joint injuries for users during exercises. The economical electronic prototype of sensing system is able to acquire the data successfully in real time which can help to make a correct decision. It can also be found in Figure 2 and 3 that playing basket had the greatest risk of knee fatigue in these four sports due to its fast running and strong physical confrontation while playing table tennis had the lowest risk, which is consistent with previous report [3]. Furthermore, female gender and high BMI value are two factors to increase the risk of knee injuries. From the scale scores of participants, the designed sensing system is proved to be able to prevent exercisers from knee joint injuries caused by fatigue. However, only using human perception to prevent fatigue of knee joint and avoid injury during exercise has a risk of failure.

4. Conclusions

In order to reduce the risk of knee injuries during exercise, a wearable system with STM32 microcontroller and multiple sensors was developed to acquire the parameters of knee joint. Then an acceleration-weighted curve fitting estimation was proposed to estimate the fatigue state. According to the experimental results, the system is helpful to prevent knee joint from injuries induced by excessive exercise and lead the users to take a suitable exercise rhythm, intensity and time.

5. Materials and Methods

Because the fatigue state of knee joint is affected by the exercise load and the degree of flexion and extension, it can be estimated and predicted according to the moving parameters. In this paper, exercise load and flexion angle of knee joint are taken into consideration, and an acceleration-weighted

curve fitting method is introduced to estimate and predict the percentage of knee fatigue. Then the excessive load during exercise is able to be avoided and the knee joint can be protected.

5.1. Mechanism and Characterization of Knee Injury

The knee joint is composed of the lower end of the femur, the upper end of the tibia and the patella with many ligaments and muscles around it. The main ligaments are medial collateral ligament (MCL), lateral collateral ligament (LCL), and anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), etc. Although the fibula does not participate in the formation of the knee joint, it has a role in the stability of the knee joint that cannot be ignored because of the origin of the lateral collateral ligament [12]. Stability maintaining mechanism of knee joint includes active stabilizing structure, passive stabilizing structure and innervation [13]. The active stabilization structure includes the muscles and skin around the knee joint; the passive stabilization structure includes the knee ligament, joint capsule, meniscus, articular cartilage, etc. Both of them are under the control of the nervous system to jointly maintain the stability of the knee joint. Passive stabilization structure is the basis for maintaining knee joint stability, so that the structure of each part of the knee joint moves according to a certain direction with participation of the active stabilization structure and innervation.

The knee joint is an approximate ginglymus, whose range of flexion and extension in the sagittal plane is larger, while the range of motion in the other two planes is smaller [14]. The range of motion of a normal knee joint is defined as the steady range of knee, that is, the range of motion of normal adduction, abduction, internal rotation, external rotation, and hyperextension. When the range of motion exceeds the normal one, the knee joint at this time is considered to be in an unstable state called instability. Injuries to the knee include bone, cartilage, and ligament injuries. There are many ligament injuries, and bone or cartilage injuries are generally combined with one or several ligament injuries [1, 15].

Common knee injuries include ligament injury, meniscus injury, and patella strain [13]. Ligament injuries mostly occur in basketball, football and other ball sports, as well as gymnastics and running [16]. In these exercises, the knee joint is often in a state of flexion. The calf suddenly abducts and

externally rotates, or the foot and calf are fixed, and the thigh suddenly rotates and adducts. This is very likely to cause damage to the medial collateral ligament of the knee joint. Most of the collateral ligaments are damaged at the same time as the joint capsule, cruciate ligament, or meniscus. After the injury, the knee joint was partially swollen, and the flexion and extension function was limited. The meniscus injury is due to the inconsistent movement of the medial and lateral meniscus when the knee is suddenly extended from the flexed position. The misalignment of the thigh and calf positions will squeeze the meniscus, causing tearing or abrasive chronic injury of the meniscus. Furthermore, the patella strain is mainly due to the repeated flexion and extension of the knee joint, which causes the corresponding joint surface of the patella and femur to be abnormally misaligned, and the impact of the twisting and friction causes local tissue and cell metabolism abnormalities.

Excessive exercise and fatigue of the knee joint have been shown to significantly increase the risk of knee injury [4, 17]. While the knee joint is gradually fatigued, the flexion angle and frequency of its movement will slightly decrease [1]. By observing the changes of these external parameters, combined with the corresponding exercise data, the progressive degree of knee fatigue can be analysed and predicted, then the exercise plan is able to be adjusted in time to reduce the risk of knee injuries.

5.2. Comprehensive load for knee joint

The knee joint fatigue is closely related to the contact force, flexion angle and moving frequency of the joint. During the exercise, the greater the contact force, the larger the flexion angle, and the higher the moving frequency is, the faster the knee joint will be fatigue. Thus, a comprehensive load formula is proposed to estimate the total burden of knee joint during sports involving the three factors as show in Equation (1).

$$l^t = \varepsilon \cdot k^{\rho \cdot \Delta t_w / \Delta t_g} \cdot b^{(BMI - \delta)} \cdot (P - P_{bm}) \cdot (C - C_{bm}) \quad (1)$$

where l^t is comprehensive load at time slice t ; P represents the maximum plantar pressure acquired by sensors on the insoles in a small sampling time window around the time slice t , which reflects the contact force of knee joint; P_{bm} denotes the benchmark value of plantar pressure which is sampled during standing still of user; C is the maximum radian of flexion angle obtained by flex sensors in a

small sampling time window around the time slice t ; C_{bm} is the benchmark value of flexion angle sampled during standing still of user; BMI represents body mass index, which is currently the most commonly used tool in the world to measure whether a person is too thin or too fat. The highest BMI value for normal weight is usually 25 in the world and 24 in China; δ is an adjustment parameter specified by the user; k denotes the base of an exponential function used to adjust the shape of the curve; Δt_{nr} represents the interval time of knee joint flexion sampled under usual walking state of the user; Δt_g is the interval time between the last knee flexion and the current one, used to describe the frequency of knee motion; ρ is an adjustment factor, specified by the user; b denotes the base of another exponential function used to adjust the shape of the curve; ε is also an adjustment factors, specified by the user. Before each experimental test, there needs to be a calibration procedure to acquire the parameter Δt_{nr} , P_{bm} and C_{bm} automatically from the user for the system through standing still and normal walking.

$$s^t = \int_0^t l^t dt \quad (2)$$

As shown in Equation (2), the comprehensive load l^t accumulates over time to make total load s^t and the increase of flexion angle, plantar pressure and motion frequency will accelerate accumulation of the value.

5.3. Acceleration-weighted curve fitting estimation

Because the knee fatigue is closely related to the active intensity of the muscles around the joint, the acceleration of the end of the tibial, which is measured by the acceleration sensor MPU-6050, can be viewed as an indicator of the muscle activity in the exercises. A higher acceleration value may increase the fatigue of the knee joint. Thus, this value can be taken as a weight in the fitting estimation. A proportional-integral (PI) controller [18] is introduced to involve the influence of strenuous muscle. In addition to affecting curve fitting through proportional term, continuous intense muscle movements also produce cumulative effects through integral term. The longer the duration, the greater the cumulative impact on the knee fatigue. As shown in Equation (3), $\Delta a(t)$ represents the acceleration

226 redundancy at time t which exceeds the threshold a_{thr} , and it can be got in calibration procedure under
 227 normal walking of user . Equation (4) shows the computational formula of PI controller.

$$\Delta a(t) = a(t) - a_{thr} \quad (3)$$

$$w(t) = K_p \left[\Delta a(t) + \frac{1}{T_I} \int_0^t \Delta a(\tau) d\tau \right] \quad (4)$$

228 where K_p represents the proportional gain, T_I denotes the integral time and $w(t)$ is the acceleration
 229 redundancy at time t which can be used as weight in the curve fitting. Because the Equation (4) can
 230 only be used in analogue systems, the integral component should be discretized for the digital
 231 equipment. Equation (5) shows the formula for conversion from the integral term to the sum of discrete
 232 errors:

$$\int_0^t \Delta a(\tau) d\tau = \sum_{j=0}^n \Delta a(j) \cdot \Delta t = T \sum_{j=0}^n \Delta a(j) \quad (5)$$

233 where $\Delta t = T$ represents the sampling period. In our experiments, the value of T is set to 1. Equation (5)
 234 can then be rewritten in discrete form as Equation (6):

$$w(k) = K_p \left[\Delta a(k) + \frac{T}{T_I} \sum_{j=0}^n \Delta a(j) \right] \quad (6)$$

235 According to Equation (7), Equation (6) can be further converted to the incremental form as
 236 Equation (8). That formula can simplify the calculation and save storage space.

$$w(k) - w(k-1) = K_p \left[\Delta a(k) - \Delta a(k-1) + \frac{T}{T_I} \Delta a(k) \right] \quad (7)$$

$$w(k) = w(k-1) + K_p \left[\Delta a(k) - \Delta a(k-1) \right] + K_I \Delta a(k) \quad (8)$$

237 where $K_I = K_p(T/T_I)$ is the integral coefficient. Then each $w(k)$ should be standardized within the array
 238 W which is consist of all the $w(k)$ values following Equation (9), where $Max(W)$ represents the
 239 maximum element inside the array and $Min(W)$ is the minimum one. Furthermore, the array W_{norm} is
 240 made of all the $w_{norm}(k)$ values and can be used for the next weighted curve fitting step.

$$w_{norm}(k) = \frac{w(k)}{Max(W) - Min(W)} \quad (9)$$

After obtaining the normalized acceleration redundancy $w_{norm}(i)$, the weighted curve fitting is able to be run on the database to figure out the prediction of knee fatigue using Equation (10).

$$\hat{w} = (S^T W_{norm} S)^{-1} S^T W_{norm} F \quad (10)$$

$$W_{norm} = \begin{bmatrix} w_{norm}(1) & 0 & \cdots & 0 \\ 0 & w_{norm}(2) & & \\ \vdots & & \ddots & \\ 0 & & & w_{norm}(i) \end{bmatrix} \quad (11)$$

where $\hat{w}$ represents the fitting coefficient; S denotes the vector of total load s^i at each point; F is the vectors of knee fatigue percentage f^i ; W_{norm} is a weight diagonal matrix as shown in Equation (11) containing acceleration redundancy $w_{norm}(i)$ as its elements.

5.4. Fatigue judgement and predication

Due to the fact that knee fatigue will be reflected in the peak knee flexion angle [1], the angle can be used to help estimate the degree of knee fatigue. However, a key function of the system is to calculate the exercise load on the knee joint and evaluate the suitable duration for different exercises. Thus, the system needs to find the mapping from the total load s^t to the percentage of knee fatigue f^t at time slice t using the peak flexion angle as a tool. From the initial moment to the latest moment in which the knee joint is fatigue, the peak knee flexion reduces nearly 10 degree [1]. According to this basis, the mapping from the total load to the percentage of knee fatigue can be built in a calibration procedure. In that procedure, let the participant do sport until he feels tired of his knee joint. During that process, at the exact time of each 1 degree reduction of the peak knee flexion, the corresponding total load s^i is calculated, where i is a serial number. Then the percentage of knee fatigue f^i is estimated by the peak knee flexion degree and the pair (s^i, f^i) can be viewed as a point in the mapping relationship. After acquiring these (s^i, f^i) key points, the cubic polynomial fitting can be performed to finish the whole curve of the mapping from s^t to f^t .

Figure 4. The sensing and predicting procedure for knee fatigue judgment.

The whole sensing and predicting procedure is shown in Figure 4 for getting the fitting coefficient $\hat{w}$. After the calibration procedure and mapping building, C , P and $w(t)$ are sensed by the device to evaluate the current percentage of knee fatigue. For that purpose, a dealing time window, which can be set to 1, 2, 3 or 5 minutes in usual, is needed for finding key points in the estimation. At the end of each window, the data acquired before will be calculated to find the fitting coefficient $\hat{w}$ and the predicting curve will be refreshed. Then the healthy remaining time t_{rem} which indicates the suitable time left for the current exercise state without knee injury can be estimated by Equation (12), where f^{end} represents the final fatigue state of knee decided by user; the $\hat{w}$ is the fitting coefficient; the s^{now} is

the total load at this moment and l^{now} denotes the comprehensive load value at current time. The healthy remaining time t_{rem} can be used to warn the user that how much time is left before knee injury under the current exercise burden.

$$t_{rem} = (f^{end} / \hat{w} - s^{now}) / l^{now} \quad (12)$$

Figure 5. (a) Illustration of the three kinds of sensors used in the sensing device; (b) Illustration of the hardware of the wearable device; (c) Illustration of the wearable accessories with sensors of the device; (d) Illustration of the shoes with sensors of the device; (e) Illustration of the wearing situation of the sensing device.

5.5. Wearable Sensing Device for Knee Joint

In order to acquire the exercise data in real time, a wearable sensing device is implemented on the STM32F103 microcontroller platform from ST Microelectronics Corporation (Geneva, Switzerland). As shown in Figure 5(a) three kinds of sensors are adopted in the device. The Flexiforce A301 is a pressure sensor from Tekscan Corporation (Boston, US) with only 0.203 mm thickness and less than 5 ms response time, which can be deployed on the insole of the shoe to measure the plantar pressure as

shown in Figure 5(c) and (d). A Flex Sensor 4.5" from Spectra-Symbol Corporation (Salt Lake City, US) is used to reflect the flexion angle of knee joint. An MPU-6050 module from InvenSense Corporation (Sunnyvale, US) containing a 3-axis gyroscope and a 3-axis accelerometer is adopted to acquire the acceleration of the end of the tibial for weighted curve fitting. The hardware of the sensing device is shown in Figure 5(b), in which the integrated operational amplifier OPA333 from Texas Instrument (Dallas, US) is designed to regulate the input signal. A BC417143 Bluetooth module from Cambridge Silicon Radio (Cambridge, UK) is used to send messages out through wireless. The Figure 5(e) shows the wearing situation of the device and with the help of it the parameters of knee joint can be measured during sports and the knee fatigue state is able to be estimated.

5.6. Experiment and participants

The experiments were performed involving 24 healthy volunteers (12 males, 12 females; for male, age = 22.9 ± 0.8 years, height 174.5 ± 3.3 cm, body mass 67.1 ± 6.8 kg; for female, age = 23.2 ± 0.9 years, height 162.9 ± 2.9 cm, body mass 55.4 ± 6.9 kg) without heart disease, nervous system disease, unsound limbs, etc. Four popular exercises in daily life are adopted for the tests, including running, badminton, table tennis and basketball. Participants were excluded if they had any pain (acute or chronic) during sports. Flexion angle of knee, plantar pressure and the acceleration of the end of the tibial were sensed by the device and involved in the estimation and predication of knee fatigue after mean filtering. For the experiments, the parameters of the system were set as follow: $\varepsilon=\rho=1$, $k=b=e$ (the natural logarithm), $\delta=24$, $K_P = 3$, $T_I = 6$, $T = 1$ for the $w(k)$ calculation, the sampling time window was set to 1 second and the dealing time window was set to 2 minutes. A calibration procedure was performed before testing to get parameter Δt_{nr} , P_{bm} , C_{bm} , a_{thr} and build the mapping from total load to knee fatigue percentage. The designed system showed warning messages to participants when the fatigue degree reached 60 percent, provided the estimated left time for healthy exercise, and the participants stopped the exercise at 80 percent of the knee fatigue. There are two kinds of test mode, the test without break and with break. In the mode without break, the participants do continuous exercise without break until stopping time. While, in the mode with break, the participants make a 5-

minute break after 20 minutes of exercise and continue to do the exercise. The exercising time for these separate parts is added to be counted as the total duration.

The whole procedure of experiment was divided into two stages. In the first stage, all the participants were organized into a same group and equipped fatigue predicting devices for warning. All the participants were asked to attend those four kinds of exercises every day in the two test mode with full recovery and the whole testing procedure lasted two weeks. During running exercise the participants were asked to keep a 2.3 m/s pace. The predicting capability of the device, the gender-comparable situation, and the influence of BMI and break during exercises were studied in this stage.

In the second stage, the participants were divided into two groups, testing group (6 males, 6 females; age = 23.2 ± 0.7 years, height 168.9 ± 6.7 cm, body mass 61.0 ± 9.1 kg) and control group (6 males, 6 females; age = 22.9 ± 0.9 years, height 168.5 ± 6.3 cm, body mass 61.5 ± 8.8 kg). The participants in testing group equipped the sensing devices and stopped the exercise at 80 percent of the knee fatigue. However, the participants in control group had not stopped their exercise until they felt tired in leg or knee by themselves. All the participants were asked to play basketball at least once every day and that procedure lasted two weeks with the same parameters of the first stage but without break. Data were acquired through the designed hardware and the average values were taken for analysis. Moreover, the Lysholm score [19, 20] and the International Knee Documentation Committee (IKDC) score [21, 22] of the participants were judged by two independent experienced orthopedists from the Department of Orthopedics, Fujian Medical University Union Hospital. After that, the participants were given a three-month rest to restore their knee joints for the next running test. Before the running test, these two scale scores of the participants were evaluated to ensure complete recovery of their knee joints. All the setting of the running test was just the same as the playing basketball. In addition, Lysholm score is a condition-specific score for evaluating knee ligament injury and widely used in various knee diseases. It is simple, non-traumatic and easy to be accepted. IKDC has relatively high reliability, effectiveness and sensitivity for the assessment of ligament injuries, especially anterior cruciate ligament injuries and defects. Thus, it is suitable for evaluating post-exercise injuries of knee joint.

Abbreviations

337 ACL: anterior cruciate ligament; MCL: medial collateral ligament; LCL: lateral collateral ligament; PI: proportional-integral; BMI: body
338 mass index; IKDC: International Knee Documentation Committee.

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342 **Authors' contributions**

343 JX, TZ: Conceptualization, Investigation, Supervision, Methodology, Formal analysis, Funding acquisition, Resources, Writing - original
344 draft, Writing - review & editing, Visualization, Software. JC: Investigation, Data curation. XH: Investigation, Formal analysis. PW:
345 Investigation. All authors read and approved the final manuscript.

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350 **Availability of data and materials**

351 The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

352 **Ethics approval and consent to participate**

353 Not applicable.

354 **Consent for publication**

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356 **Competing interests**

357 The authors declare that they have no competing interests.

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Figures

Figure 1

(a) Illustration of flexion angle data acquired by the device in running; (b) Illustration of plantar pressure data acquired by the device in running; (c) Illustration of predicting curve of knee fatigue in the 38th minute for running; (d) Illustration of flexion angle data acquired by the device in playing basketball; (e) Illustration of plantar pressure data acquired by the device in playing basketball; (f) Illustration of predicting curve of knee fatigue in the 24th minute for playing basketball.

Figure 2

(a) The healthy time of different genders for knee joint during the four exercises without break; (b) The healthy time of different BMI situation for knee joint during the four exercises without break; (c) The healthy time for knee joint during the four exercises with and without break. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

Figure 3

(a) Lysholm scores of testing and control groups before and after playing basketball and running; (b) IKDC scores of testing and control groups before and after playing basketball and running; (c) Lysholm scores of control group for different genders before and after playing basketball and running; (d) IKDC scores of control group for different genders before and after playing basketball and running; (e) Lysholm scores of control group for different BMI situation before and after playing basketball and running; (f) IKDC scores of control group for different BMI situation before and after playing basketball and running. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

Figure 4

The sensing and predicting procedure for knee fatigue judgment.

Figure 5

(a) Illustration of the three kinds of sensors used in the sensing device; (b) Illustration of the hardware of the wearable device; (c) Illustration of the wearable accessories with sensors of the device; (d) Illustration of the shoes with sensors of the device; (e) Illustration of the wearing situation of the sensing device.