

Statistical analysis of range of motion and surface electromyography data for a knee rehabilitation device

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ABSTRACT

This work introduces a statistical analysis of knee range of motion (ROM) and surface electromyography (EMG) data gathered from a knee extension rehabilitation device. Real-time ROM and EMG signals of rehabilitation users are measured using a single angle sensor and a two-channel EMG device (for the vastus lateralis and vastus medialis muscles). These signals are collected by the NI-myRIO embedded device in accordance with the designed rehabilitation program. The main contribution and novelty of this study is that real-time signals are automatically processed and transformed into statistical data for use by users and medical experts. A solution for extracting raw signals is proposed, in which several statistical functions such as range, mean, standard deviation, skewness, percentiles, interquartile range, and total knee holding times above the threshold level, are implemented and applied. The proposed solution is tested using data acquired from healthy people, which includes gender, age, body size, knee side, exercise behavior, and surgical experience. Results indicated that real-time signals and related statistical data on the knee's performance can be efficiently monitored. With this solution, rehabilitation users can practice and learn about their knee performance, while medical experts can evaluate the data and design the best rehabilitation program for users.

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1. INTRODUCTION

Correct knee joint mobility is critical for an individual's health [1]. Walking, standing, sitting, climbing stairs, driving, playing sports, and other daily activities all involve the knee. Because the knee joint supports the weight of the human body and is essential for human movement, knee injuries can make it difficult to conduct many everyday living tasks [2]. Furthermore, age and the advent of certain pathologies, i.e., osteoarthritis (OA), are variables that can cause significant and serious injuries [3].

OA [4], [5] is one of the most frequent musculoskeletal conditions in the adult population, with the knee joint being the most commonly diagnosed [6]. The treatment of OA is interdisciplinary and varies according to the state of the degenerative processes. Rehabilitation and exercise to strengthen the knee muscles are significant therapies for OA. It should be noted that OA is one of the most common knee joint mobility problems. There are also other disorders and symptoms associated with knee joint mobility issues, and individuals in this category require rehabilitation treatment [7]. Furthermore, in sports medicine, reliable measurements and monitors of knee extensor and flexor muscle strength are required to determine the impact of therapeutic interventions or the impacts of physical training [8]–[10]. According to the requirements and

importance of the issues mentioned above, suitable monitoring and rehabilitation tools and methods to assess and assist knee joint mobility patients are required. Because of advances in sensing techniques, lower-cost circuits, and networking technologies, autonomous and efficient monitoring and rehabilitation systems to aid patients can be built [11]–[13].

To measure and monitor knee joint movement, range of motion (ROM) is a clinical metric often used by medical experts [14], [15]. Accurate ROM measurements are critical for diagnosis, symptom progression monitoring, clinical decision-making, therapeutic feedback analysis, surgery planning, and impairment determination [16], [17]. Furthermore, it assists the patient in monitoring their progress while receiving medical care and can be used as a rehabilitation objective. Not only ROM but also electromyography (EMG) measurements have been taken into account for this task. Because EMG provides information about muscle activity [18], EMG devices can be used in a variety of fields, including biomedical, physiotherapy, and sports performance applications, where it is critical to assess muscle behavior throughout the task [19], based on changes in the electrical signal [20], [21]. According to the literature review, the development and evaluation of knee ROM and EMG measurements and systems are summarized in Table 1, and a comparison of the existing works and this work is also provided in the table.

Table 1. A summary of related works

Works	Major contributions	Sensors/Equipment
[22]	Knee joint resistance torque during passive motion was measured using an isokinetic machine or Biodex equipment.	– Isokinetic machine (i.e., the Biodex) – EMG electrodes; for quadriceps femoris muscle and hamstrings muscle
[23]	A method to predict the dynamic knee joint ROM based on the external load applied during leg extension using an EMG-driven musculoskeletal model was presented.	– Dynamometer – EMG electrodes; for semimembranosus, biceps femoris long head, rectus femoris, vastus lateralis (VL), vastus medialis (VM), gastrocnemius lateralis, and gastrocnemius medialis
[24]	The relationship between isometric force and surface EMG of quadriceps femoris muscles in single-joint knee extension and multi-joint leg push activities was examined.	– Dynamometer – EMG electrodes; for VL, VM, biceps femoris, and rectus femoris muscles
[25]	The EMG angle relationship of the quadriceps muscle during knee extensions was investigated.	– Electronic inclinometers – EMG electrodes; rectus femoris, VL, and VM
[26]	– A knee extension monitoring and rehabilitation system using a two-channel surface EMG device and an angle sensor was presented. – Real-time ROM and EMG signals can be obtained. – A knee rehabilitation program could be defined and flexibly set for rehabilitation training.	– Angle sensor – Surface EMG electrodes; for VL and VM muscles – NI-myRIO embedded device with the rehabilitation program using LabVIEW
This work	– Real-time ROM and EMG signals are automatically transformed into statistical data using several statistical functions. – Extracted information from raw signals can be provided for broader usage. – Users and medical experts can review, select, and focus their attention on the specific data that they want to focus on and track.	– Angle sensor – Surface EMG electrodes; for VL and VM muscles – NI-myRIO embedded device with the rehabilitation program using LabVIEW

Igari *et al.* [22] presented the development of a method for measuring knee joint resistance torque using an isokinetic machine or Biodex equipment. The resistance torque during passive joint motion could be measured by correcting for angle, gravity, and inertia based on the angle and torque that were output by the Biodex. Additionally, the EMG signals were measured simultaneously by monitoring the output of a potentiometer mounted on the arm of the Biodex. With this solution, both ROM and EMG could be measured simultaneously. Son *et al.* [23] introduced a method to predict the dynamic knee joint ROM based on the external load applied during leg extension using an EMG-driven musculoskeletal model. It is reported that the ROM varied according to the external loads applied to the knee joint during exercise. Additionally, the authors expected that their approach would be employed to design exercise and rehabilitation protocols for the elderly.

The relationship between isometric force and surface EMG of quadriceps femoris muscles in single-joint knee extension and multi-joint leg push activities was examined in [24]. At 20%, 40%, 60%, 80%, and 100% maximal contraction, nine healthy subjects performed unilateral activities at a knee angle of 90°. EMGs were also recorded from the vastus lateralis (VL), vastus medialis (VM), biceps femoris, and rectus femoris muscles. Based on their data, the authors concluded that all of the muscles under consideration appeared to have a comparable EMG/force relationship at a 90° angle to the knee. In [25], the EMG angle relationship of the quadriceps muscle during knee extensions performed with elastic tubing and isotonic strength training equipment was investigated. There were seven females and nine males tested. During the concentric and eccentric contraction phases of a knee extension, EMG was recorded, and knee joint angle was measured using

inclinometers. When the machine and elastic resistance exercises were compared, there were no differences in the peak EMG of the VL, VM, and rectus femoris muscles during the concentric contraction phase.

Finally, in our previous work [26], a knee extension monitoring and rehabilitation system was presented. Using a two-channel surface EMG device and an angle sensor, this system could measure VL and VM EMG signals as well as ROM signals. Furthermore, the knee rehabilitation program was presented, which was implemented on the NI-myRIO device using the LabVIEW tool and could be built and modified freely based on the needs of physical therapists and physicians. The results of the experiments showed real-time EMG and ROM data. The key constraint of such a study is that the acquired findings are real-time EMG and ROM data, and extracted information from raw signals should be provided for broader usage.

Based on the summarized information from the literature review described above, in this work, a statistical analysis of knee ROM and surface EMG signals for a knee extension monitoring and rehabilitation device is presented. The major contributions and novelties of this work are twofold. First, raw ROM and EMG signals measured from healthy subjects are automatically transformed into statistical data as extracted information. For this purpose, several statistical functions are implemented and applied. Here the statistical features include minimum value, maximum value, range (i.e., max-min), mean, median, mode, standard deviation, skewness, percentiles (i.e., the minimum, the 25th percentile, the 50th percentile, the 75th percentile, and the maximum), interquartile range, total knee holding times above the threshold level, mean and mode values above the threshold level, and knee movement degrees ranging from small to large. Second, the proposed solution has been evaluated on healthy volunteers, where genders, age ranges, body sizes, knee angles, exercise behaviors, and surgical experience were considered. The experimental results show statistical data as extracted information about knee movement performance. Through our solution, rehabilitation users can practice and learn about their performance during testing, while physiotherapists and physicians can review, select, and focus their attention on the specific data that they want to focus on and track for the benefit of rehabilitation users.

The structure of this paper is as follows: methods, including the knee extension monitoring and rehabilitation device, a statistical analysis of raw ROM and EMG signals, and ROM and EMG data for testing, are described in section 2. Section 3 provides results and discussion. Finally, we conclude the paper in section 4.

2. METHOD

2.1. Knee extension monitoring and rehabilitation device

The knee extension monitoring and rehabilitation device developed by our research group is shown in Figure 1. The accelerometer sensor or angle sensor module is used to measure real-time knee ROM signals, while a two-channel surface EMG device is used to detect real-time VL and VM EMG signals. The NI-myRIO is linked to both sensors for processing. Knee rehabilitation programs for this device can be set up using the LabVIEW application in the NI-myRIO [27]. The device is also linked to a data server through Wi-Fi and the Internet, where physiotherapists and physicians can evaluate the results and create the best rehabilitation program for individuals. We note that Sengchuai *et al.* [26] described the system's implementation in further detail.

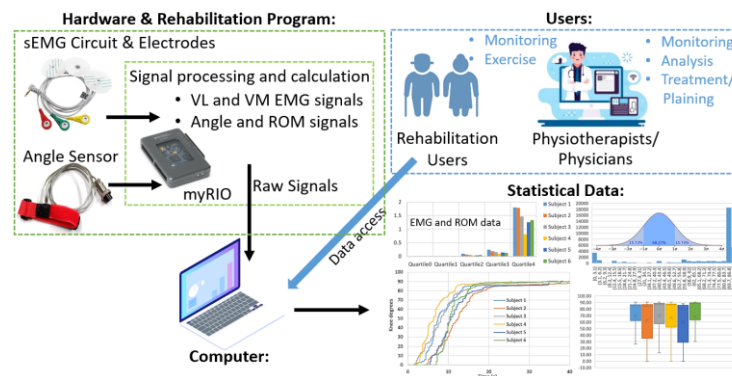


Figure 1. A system for knee extension monitoring and rehabilitation devices

During testing, the angle sensor is mounted to the ankle using the accelerometer, namely GY-521, as shown in Figure 2. A 1.0 kg sandbag is additionally attached to the ankle to increase the load on the knee

during testing and to analyze knee extension performances in accordance with the allocated rehabilitation program. The weight of the sandbag might be altered here based on the program and the experts' choices. Two electrodes are applied to the skin at the VL and VM muscles for EMG measurement [24], while one electrode is put on the hand or forearm as a reference electrode.

A test participant sits on the chair in the appropriate position recommended by experts. The subject is asked to move the leg from 0 to 90 degrees for each round of the test, where 0 and 90 degrees relate to the subject sitting and completely extending out the knee. The angle sensor data can be translated into the degree of knee movement, with the minimum and maximum degrees (i.e., θ_{min} and θ_{max}) varying depending on each user's knee movement performance. The difference between such values, or the range of knee movement degrees, is the ROM. At the same time, the EMG signals recorded from the VL and VM muscles are reported during knee movement. According to experts, these muscles were chosen for examination because they are targeted in rehabilitation due to their significance in patellar stability during knee extension. These muscles are directly related to knee pain and knee performance.

Figure 2 also shows a knee movement pattern to be examined. According to the expert's advice, the subject begins with a 0 degree knee position and then constantly extends or moves the knee to 90 degrees, or the highest degree that the subject can do. The subject maintains his or her knee at its highest peak over a period of time. Finally, the subject returns to the starting position and takes a short break. This refers to the one-round testing procedure. The subject can go to the next round until they reach the last round or one set (i.e., five rounds for this work). The real-time knee ROM and EMG signals from this test are captured, and they will be analyzed and translated into statistical data as summary information for users and experts to utilize, as detailed in the section below.

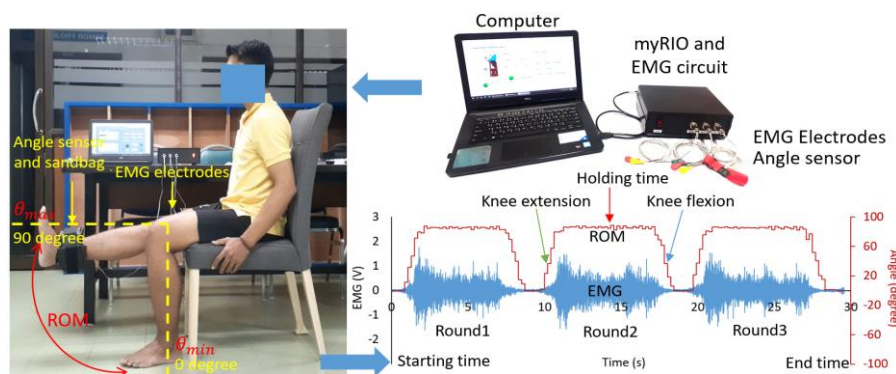


Figure 2. An example of installation setup, testing, and the ROM and VL EMG signal patterns

2.2. Statistical analysis of raw ROM and EMG signals

In this work, raw signals measured from users, including ROM and the absolute values of VL and VM EMG signals, are displayed for monitoring during the test. Moreover, the signals will be automatically transformed into statistical data as feature data using the statistical functions summarized in Table 2. Here, minimum value, maximum, range (i.e., max-min), mean, median, mode, standard deviation, skewness, percentiles (i.e., the minimum, the 25th percentile, the 50th percentile, the 75th percentile, and the maximum), inter-quartile range, total knee holding times above the threshold level, mean and mode values above the threshold level, knee movement degrees ranging from small to large, and box plots of raw ROM, VL EMG, and VM EMG signals are calculated and reported.

As demonstrated in Table 2, the mean, standard deviation, mode, and total knee holding time are also calculated for the case where the ROM is greater than 80 degrees. This is only an illustration threshold (i.e., $ROM > 80$) to be explored and evaluated. Here, the threshold level can be flexibly set to different levels, such as 50, 70, and 90, respectively (from small to high levels), based on users' and experts' requirements. For example, if rehabilitation users practice well and their knee movement performances are nearly 90 degrees or higher, the threshold level can be set to a high level. On the other hand, at the beginning of rehabilitation, a small threshold should be applied.

Our methodology allows both users and medical experts to review, select, and focus their attention on the specific data that they want to focus on and track. For example, to explore how long the user can hold his or her knee above the threshold level, $HT_{ROM > 80}$ reports this information, where it directly represents knee strength, with a strong person being able to hold his or her knee for longer periods of time. For another example, as shown in Figure 2, the ROM signal patterns and shapes measured from round 1 to round 5 may

be different. The skewness of such data will inform us of the asymmetry of a distribution, where a distribution can have right (or positive), left (or negative), or zero skewness. Quartile and interquartile range (IQR) also extract and report such information.

Table 2. A summary of the statistical functions applied to raw ROM and EMG signals

Statistical functions and descriptions	ROM	Equations	EMG for VL and VM muscles
Mean The average value of the ROM, VL EMG, and VM EMG signals	$\mu_{ROM} = \frac{1}{N} \sum_{i=1}^N \theta_i$		$\mu_{VL} = \frac{1}{N} \sum_{i=1}^N VL_i \quad \mu_{VM} = \frac{1}{N} \sum_{i=1}^N VM_i$ Note VL_i and VM_i are the absolute values
Mean; for ROM>80 The average value of the ROM, VL EMG, and VM EMG signals; the knee movement degree is greater than 80	$\mu_{ROM>80} = \frac{1}{N_j} \sum_{i=1}^{N_j} \theta_i; \text{ for } \theta_i > 80$		$\mu_{VL,ROM>80} = \frac{1}{N_j} \sum_{i=1}^{N_j} VL_i; \text{ for } \theta_i > 80$ $\mu_{VM,ROM>80} = \frac{1}{N_j} \sum_{i=1}^{N_j} VM_i; \text{ for } \theta_i > 80$
Standard deviation (SD); for ROM>80 The amount of variation in ROM, VL EMG, and VM EMG signals; knee movement degrees>80	$\sigma_{ROM>80} = \sqrt{\frac{1}{N_j} \sum_{i=1}^{N_j} (\theta_i - \mu_{ROM>80})^2}; \text{ for } \theta_i > 80$		$\sigma_{VL,ROM>80} = \sqrt{\frac{1}{N_j} \sum_{i=1}^{N_j} (VL_i - \mu_{VL,ROM>80})^2}$ $\sigma_{VM,ROM>80} = \sqrt{\frac{1}{N_j} \sum_{i=1}^{N_j} (VM_i - \mu_{VM,ROM>80})^2}; \text{ for } \theta_i > 80$
Mode; for ROM>80 The most frequent values of the ROM, VL EMG, and VM EMG signals; knee movement degrees>80	$mode_{ROM>80} [\theta_i, \dots, \theta_{N_j}]; \text{ for } \theta_i > 80$		$mode_{VL,ROM>80} [VL_i, \dots, VL_{N_j}]; \text{ for } \theta_i > 80$ $mode_{VM,ROM>80} [VM_i, \dots, VM_{N_j}]; \text{ for } \theta_i > 80$
Total knee holding time; for ROM>80 How long the user can hold his or her knee above the threshold level	$HT_{ROM>80} = \sum_{i=1}^{N_j} \Delta ht_i; \text{ for } \theta_i > 80$		-
Min The minimum values of the ROM, VL EMG, and VM EMG signals	$\min(\theta_i, \dots, \theta_N)$		$\min(VL_i, \dots, VL_N)$ $\min(VM_i, \dots, VM_N)$
Max The maximum values of the ROM, VL EMG, and VM EMG signals	$\max(\theta_i, \dots, \theta_N)$		$\max(VL_i, \dots, VL_N)$ $\max(VM_i, \dots, VM_N)$
Range (Max-Min) The range between the maximum and the minimum values of the ROM, VL EMG, and VM EMG signals	$\max(\theta_i, \dots, \theta_N) - \min(\theta_i, \dots, \theta_N)$		$\max(VL_i, \dots, VL_N) - \min(VL_i, \dots, VL_N)$ $\max(VM_i, \dots, VM_N) - \min(VM_i, \dots, VM_N)$
Median The middle value of the ROM, VL EMG, and VM EMG signals	$\text{median}(\theta_i, \dots, \theta_N)$		$\text{median}(VL_i, \dots, VL_N)$ $\text{median}(VM_i, \dots, VM_N)$
Skewness A measure of the asymmetry of the distribution of the ROM, VL EMG, and VM EMG signals	$\frac{1}{N\sigma_{ROM}^3} \sum_{i=1}^N (\theta_i - \mu_{ROM})^3$		$\frac{1}{N\sigma_{ROM}^3} \sum_{i=1}^N (VL_i - \mu_{VL})^3$ $\frac{1}{N\sigma_{ROM}^3} \sum_{i=1}^N (VM_i - \mu_{VM})^3$ Same as the equations on the left side, by changing $\theta_{i \rightarrow N}$ to $VL_{i \rightarrow N}$ or $VM_{i \rightarrow N}$
Quartile The minimum value, the 25 th percentile, the 50 th percentile, the 75 th percentile, and the maximum value of the ROM, VL EMG, and VM EMG signals Note: Box plots of ROM, VL EMG, and VM EMG are also applied, presenting the minimum, the 25 th percentile, the 50 th percentile, the 75 th percentile, and the maximum value	$\text{Quartile}(\theta_{i \rightarrow N}, 0) = \text{Percentile}(\theta_{i \rightarrow N}, 0) = \min(\theta_i, \dots, \theta_N)$ $\text{Quartile}(\theta_{i \rightarrow N}, 1) = \text{Percentile}(\theta_{i \rightarrow N}, .25)$ $\text{Quartile}(\theta_{i \rightarrow N}, 2) = \text{Percentile}(\theta_{i \rightarrow N}, .50) = \text{median}(\theta_i, \dots, \theta_N)$ $\text{Quartile}(\theta_{i \rightarrow N}, 3) = \text{Percentile}(\theta_{i \rightarrow N}, .75)$ $\text{Quartile}(\theta_{i \rightarrow N}, 4) = \text{Percentile}(\theta_{i \rightarrow N}, 1) = \max(\theta_i, \dots, \theta_N)$		
Interquartile range (IQR) The different level between the 75 th percentile and the 25 th percentile	$\text{Percentile}(\theta_{i \rightarrow N}, .75) - \text{Percentile}(\theta_{i \rightarrow N}, .25)$		$\text{Percentile}(VL_{i \rightarrow N}, .75) - \text{Percentile}(VL_{i \rightarrow N}, .25)$ $\text{Percentile}(VM_{i \rightarrow N}, .75) - \text{Percentile}(VM_{i \rightarrow N}, .25)$
The knee movement degrees ranging from small to large	Ranging from min of θ_i to max of θ_i ($\min(\theta_i, \dots, \theta_N)$ to $\max(\theta_i, \dots, \theta_N)$)		-

2.3. ROM and EMG data

The method in section 2.2 has been tested by using raw ROM and EMG data collected from our previous work [26], where the knee extension monitoring and rehabilitation device was tested with six healthy subjects and the raw ROM and VL and VM EMG signals were measured. Table 3 provides the subject's information, including gender, age, weight, the knee's side to be tested, and exercise behavior. As shown in the table, both male and female subjects with ages ranging from 26 to 50, weights ranging from 49 to 110 kg, and knee sides, are considered. Exercise behavior also informs the subject's health and is used for evaluation. We note that subject 5 underwent knee surgery on his left knee as a result of his heavy football playing. However, based on the diagnostics of physicians and physiotherapists, he can be regarded as a healthy subject at the time of testing.

Table 3. Subject information [26]

Subjects	Gender	Age (year)	Weight (kg)	Knee's side	Exercise behavior
1	Male	35	65	Right	3-5 times a week; Badminton and running
2	Male	42	72	Left	-
3	Male	50	76	Right	1-2 times a week; Running
4	Male	26	110	Right	-
5	Male	31	67	Left	3-5 times a week; Playing football
6	Female	30	49	Right	3-5 times a week; Playing aerobics and going to the gym

3. RESULTS AND DISCUSSION

Figures 3(a) and 3(b) illustrate the raw ROM and VL EMG and VM EMG signals of subject 1 (i.e., a male with a weight of 65 kg and always exercising) compared with subject 4 (i.e., a male with a weight of 110 kg and no exercise) as an example. As shown in the figure, the measured signals follow the knee movement patterns (i.e., five rounds of testing) as the subjects move their knee joints against the weight of the sandbag. In this case, both subjects can have ROMs of over 80 or nearly 90 degrees. However, the results show that subject 1's ROM signal is consistently five rounds. He can hold his knee for a longer period of time than subject 4. Also, the EMG signals captured from the VL and VM muscles provide higher amplitude levels.

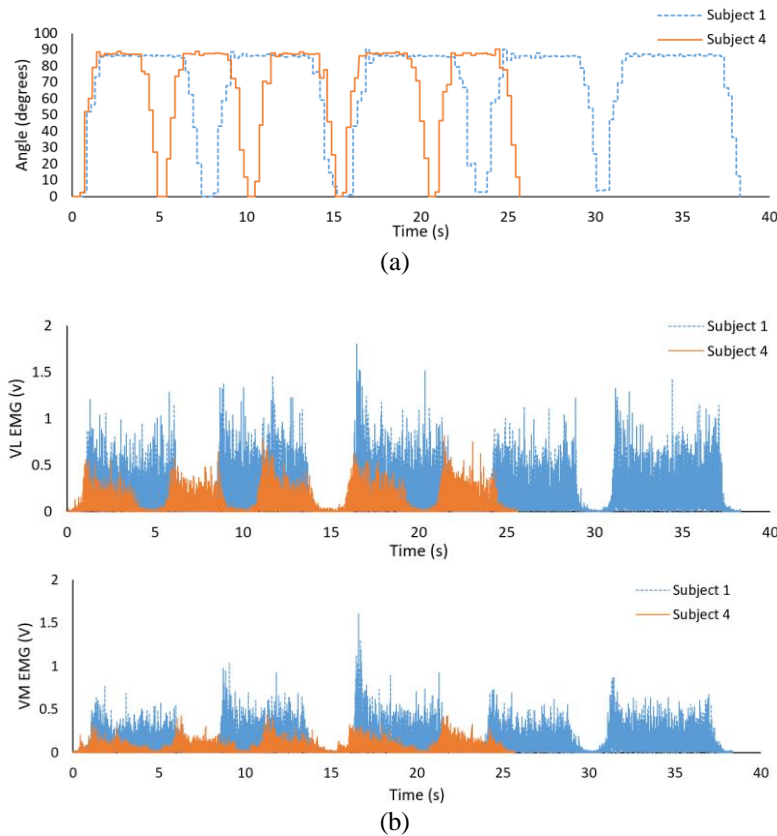


Figure 3. Examples of (a) raw ROM and (b) VL and VM EMG signals of subjects 1 and 4

Figure 4(a) demonstrates the degrees of knee movement throughout the test time, ranging from small to large for all subjects, while a comparison of subjects 2, 4, and 6 with slope and peak value consideration is shown in Figure 4(b). The results illustrate that, for five rounds of testing, subject 4 performed the test faster compared with others. He can hold his knee at its peak value, which is lower than 90 degrees, for a shorter period of time and stops his move after about 25 seconds. Subject 2, on the other hand, moves quite slowly and cannot reach 90 degrees in less than 40 seconds. For subject 6, she can hold her knee at its peak value of nearly 90 degrees for a longer period of time compared with others. The findings show that by combining Figures 3 and 4, more investigation information and a better understanding of the user’s rehabilitation behavior can be gained.

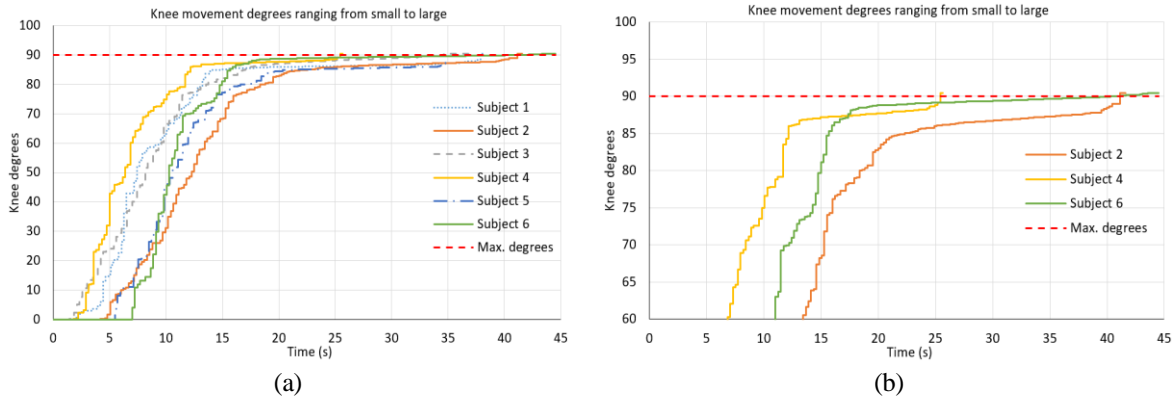


Figure 4. Knee movement degrees ranging from small to large (a) subjects 1 to 6 and (b) subjects 2, 4, and 6 with slope and peak value consideration

The statistical results applied to raw ROM, VL EMG, and VM EMG data using the statistical functions are presented below. Table 4 summarizes the ROM statistical results, including the mean value, min, max, range, median, skewness, total knee holding time for ROM>80, mode for ROM>80, and mean for ROM>80 and its standard deviation (SD). Additionally, ROM quartiles 1–4 and IQR results are also illustrated in Figures 5(a) and 5(b), respectively. The statistical results here reveal that extracted data as summarized data can be obtained. Subject 5, for example, cannot move his knee to 90 degrees since his maximum range of motion is 87.97 and his middle range of motion is 80.28. Also, for ROM>80, the mean ROM is 84.98, with the most frequent ROM value of 85.67. Furthermore, we can see from the knee holding time results that subject 5 can hold his knee for 18.18 s over 80 degrees level. Compared with subject 6, she provides better results since she can obtain 90.46 degrees for the maximum knee movement degree and 29.52 seconds for the knee holding time over 80 degrees.

Table 4. Statistical results for ROM

Subjects	Mean (degrees)	Min. (degrees)	Max. (degrees)	Range: max.-min. (degrees)	Median (degrees)	Skewness	Knee holding time; ROM>80 (s)	Mode; ROM>80 (degrees)	Mean; ROM>80 (degrees)	SD; ROM>80
1	68.87	0.00	90.46	90.46	85.89	-1.48	25.08	90.46	86.32	1.06
2	62.62	0.00	90.46	90.46	84.19	-0.97	23.24	86.56	86.30	1.94
3	69.58	0.00	90.46	90.46	86.62	-1.34	23.16	90.46	87.62	2.38
4	66.45	0.00	90.46	90.46	86.20	-1.24	13.96	84.32	87.48	0.99
5	59.89	0.00	87.97	87.97	80.28	-0.90	18.18	85.67	84.98	1.53
6	68.05	0.00	90.46	90.46	88.90	-1.26	29.52	90.46	89.10	1.35

Quartiles 1–4 and IQR results in Figure 5 provide more extracted information, and they also correlate with the above discussion. As seen in the graph, for subjects 5 and 6, since quartiles 1 (i.e., 62.99; the 25th percentile) and 3 (i.e., 89.55; the 75th percentile) of subject 6 are greater than those of subject 5, with quartiles 1 and 3 of 28.75 and 85.38, the ROM IQR of subject 6 (i.e., 26.56) is then lower than that of subject 5 (i.e., 56.64). These results show the distribution of the ROM results and can refer to the knee’s movement performance. The results here also correlate with the box plot as demonstrated in Figure 6, which presents the minimum ROM, the 25th percentile, the 50th percentile, the 75th percentile, and the maximum ROM,

respectively. We note that, as observed in Table 4 and related to the box plot results, all subjects obtain the skewness results with a negative value, which indicates the ROM distribution with an asymmetric tail extending toward the negative value. Here, the subjects can obtain the maximum ROM rather than the minimum ROM.

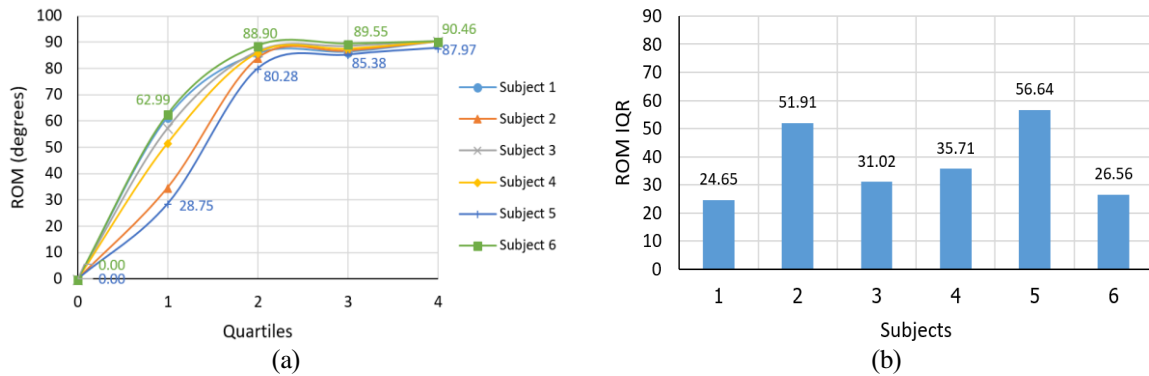


Figure 5. ROM results in terms of (a) ROM quartiles 1-4 and (b) IQR

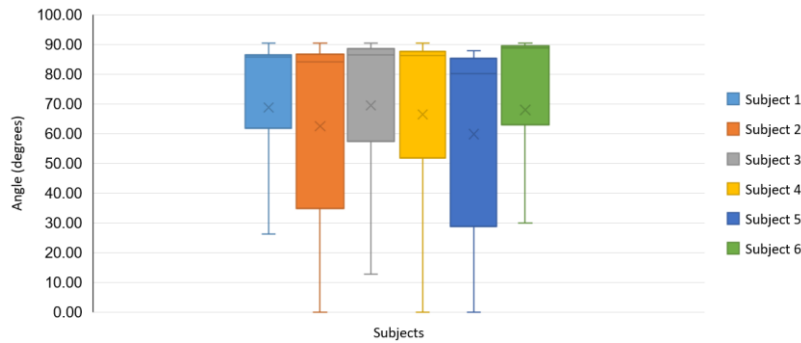


Figure 6. Box plots of ROM

The VL and VM EMG statistical results are shown in Tables 5 and 6, respectively. The results demonstrate that subject 1 obtains stronger EMG levels for both VL and VM muscles compared with others. As shown in the tables, his mean and maximum EMG levels are 0.16 and 1.80 for VL and 0.11 and 1.61 for VM, respectively, whereas subject 4 obtains 0.07 and 0.82 for VL and 0.04 and 0.43 for VM. The mean EMG for ROM>80 also confirms this discussion, as subject 1 can maintain his knee above ROM 80 degrees with a high EMG level (i.e., 0.21 for VL and 0.13 for VM). We note that, as seen in the tables, all subjects obtain a higher VL EMG level than the VM EMG level. The ratio of the VL range to the VM range in the last column of Table 6 also confirms this information. By considering this ratio, subject 1 provides more balance between VL and VM EMG levels since the ratio is 1.12, which is calculated from 1.80/1.61. We note that the extracted data from VL and VM EMG quartiles 1-4 in Figures 7(a) and 7(b), the IQR results in Tables 5 and 6, and the box plots of VL and VM EMG in Figures 8(a) and 8(b) all point in the same direction and all confirm our previous discussion.

Table 5. Statistical results for VL EMG

Sub ject	VL EMG							Mean EMG; ROM>80 (V)	SD; ROM>80
	Mean EMG (V)	Min. EMG (V)	Max. EMG (V)	Range EMG: max-min (V)	Median EMG (V)	IQR	Skewness		
1	0.16	0.00	1.80	1.80	0.10	0.23	1.81	0.21	0.18
2	0.14	0.00	1.78	1.78	0.07	0.18	2.18	0.20	0.18
3	0.11	0.00	1.46	1.46	0.05	0.15	2.16	0.17	0.16
4	0.07	0.00	0.82	0.82	0.03	0.09	2.18	0.09	0.08
5	0.10	0.00	1.25	1.25	0.04	0.14	2.17	0.16	0.15
6	0.09	0.00	1.33	1.33	0.05	0.12	2.17	0.11	0.10

Table 6. Statistical results for VM EMG

Subject	VM EMG							Mean EMG; ROM>80 (V)	SD; ROM >80	Ratio: VL/VM range
	Mean EMG (V)	Min. EMG (V)	Max. EMG (V)	Range EMG: max-min (V)	Median EMG (V)	IQR	Skewness			
1	0.11	0.00	1.61	1.61	0.07	0.14	2.05	0.13	0.11	1.12
2	0.09	0.00	1.20	1.20	0.05	0.10	2.41	0.12	0.11	1.48
3	0.08	0.00	1.26	1.26	0.04	0.10	2.51	0.11	0.11	1.16
4	0.04	0.00	0.43	0.43	0.03	0.05	2.16	0.05	0.05	1.88
5	0.05	0.00	0.53	0.53	0.03	0.05	2.01	0.07	0.05	2.36
6	0.09	0.00	0.96	0.96	0.06	0.12	1.98	0.11	0.10	1.39

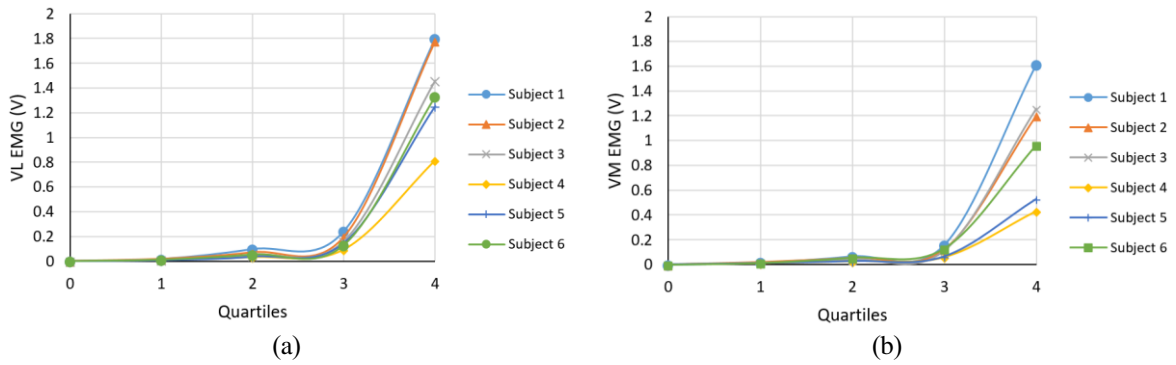


Figure 7. EMG quartiles 1-4 (a) VL EMG and (b) VM EMG

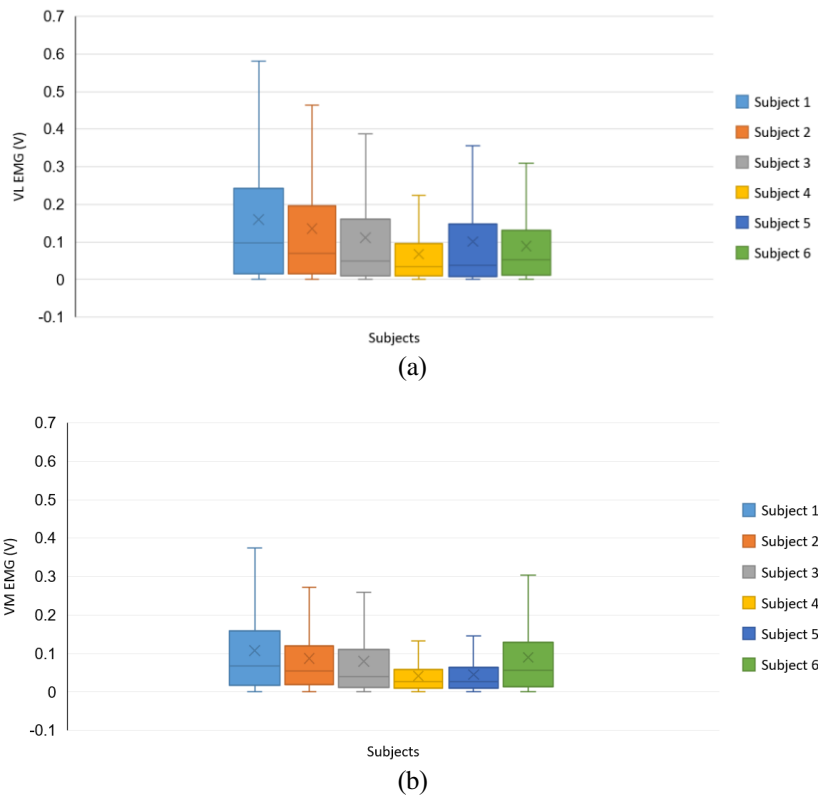


Figure 8. Box plots of EMG (a) VL EMG and (b) VM EMG

4. CONCLUSION

This work presents the statistical analysis of knee ROM and surface EMG signals for the knee extension monitoring and rehabilitation device. The real-time ROM and EMG signals measured from healthy

subjects are automatically transformed into statistical data as extracted information for users, physiotherapists, and physicians. For this purpose, several statistical functions are implemented and applied. Experimental results demonstrate real-time ROM, VL EMG, and VM EMG signals, and extract information related to knee movement performance. Additionally, a comparison and evaluation of the results obtained from all subjects are also reported. With our proposed methodology and results presented in this work, rehabilitation users can practice and learn about their performance during testing, while physiotherapists and physicians can review, select, and focus their attention on the specific data for the benefit of rehabilitation users. In future work, the proposed solution with statistical functions will be applied to the ROM and EMG signals gathered from patients with various knee movement problems. In addition, a graphical user interface (GUI) to display results and flexibly support related statistical functions will be implemented.

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REFERENCES

- [1] H. Nonaka *et al.*, "Age-related changes in the interactive mobility of the hip and knee joints: a geometrical analysis," *Gait and Posture*, vol. 15, no. 3, pp. 236–243, Jun. 2002, doi: 10.1016/S0966-6362(01)00191-6.
- [2] J. Yao *et al.*, "Lower limb joint motion and muscle force in treadmill and over-ground exercise," *BioMedical Engineering OnLine*, vol. 18, no. 1, Dec. 2019, doi: 10.1186/s12938-019-0708-4.
- [3] J. Di Tocco *et al.*, "Wearable device based on a flexible conductive textile for knee joint movements monitoring," *IEEE Sensors Journal*, vol. 21, no. 23, pp. 26655–26664, Dec. 2021, doi: 10.1109/JSEN.2021.3122585.
- [4] M. van der Esch, M. Steultjens, J. Harlaar, D. Knol, W. Lems, and J. Dekker, "Joint proprioception, muscle strength, and functional ability in patients with osteoarthritis of the knee," *Arthritis and Rheumatism*, vol. 57, no. 5, pp. 787–793, Jun. 2007, doi: 10.1002/art.22779.
- [5] Y. Suzuki *et al.*, "Home exercise therapy to improve muscle strength and joint flexibility effectively treats pre-radiographic knee OA in community-dwelling elderly: a randomized controlled trial," *Clinical Rheumatology*, vol. 38, no. 1, pp. 133–141, Jan. 2019, doi: 10.1007/s10067-018-4263-3.
- [6] A. E. Peters, R. Akhtar, E. J. Comerford, and K. T. Bates, "The effect of ageing and osteoarthritis on the mechanical properties of cartilage and bone in the human knee joint," *Scientific Reports*, vol. 8, no. 1, Apr. 2018, doi: 10.1038/s41598-018-24258-6.
- [7] J. Byra and K. Czernicki, "The effectiveness of virtual reality rehabilitation in patients with knee and hip osteoarthritis," *Journal of Clinical Medicine*, vol. 9, no. 8, Aug. 2020, doi: 10.3390/jcm9082639.
- [8] G. Reurink *et al.*, "Reliability of the active and passive knee extension test in acute hamstring injuries," *The American Journal of Sports Medicine*, vol. 41, no. 8, pp. 1757–1761, Aug. 2013, doi: 10.1177/0363546513490650.
- [9] C. M. Norris and M. Matthews, "Inter-tester reliability of a self-monitored active knee extension test," *Journal of Bodywork and Movement Therapies*, vol. 9, no. 4, pp. 256–259, Oct. 2005, doi: 10.1016/j.jbmt.2005.06.002.
- [10] A. T. Peebles, K. R. Ford, J. B. Taylor, J. M. Hart, L. P. Sands, and R. M. Queen, "Using force sensing insoles to predict kinetic knee symmetry during a stop jump," *Journal of Biomechanics*, vol. 95, Oct. 2019, doi: 10.1016/j.jbiomech.2019.07.037.
- [11] A. I. Faisal, S. Majumder, R. Scott, T. Mondal, D. Cowan, and M. J. Deen, "A simple, low-cost multi-sensor-based smart wearable knee monitoring system," *IEEE Sensors Journal*, vol. 21, no. 6, pp. 8253–8266, Mar. 2021, doi: 10.1109/JSEN.2020.3044784.
- [12] A. Akhavanhezaveh and R. Abbasi-Kesbi, "Diagnosing gait disorders based on angular variations of knee and ankle joints utilizing a developed wearable motion sensor," *Healthcare Technology Letters*, vol. 8, no. 5, pp. 118–127, Oct. 2021, doi: 10.1049/htl2.12015.
- [13] W. Jiang *et al.*, "A wearable tele-health system towards monitoring COVID-19 and chronic diseases," *IEEE Reviews in Biomedical Engineering*, vol. 15, pp. 61–84, 2022, doi: 10.1109/RBME.2021.3069815.
- [14] A. Kornuijt, G. J. L. de Kort, D. Das, A. F. Lenssen, and W. van der Weegen, "Recovery of knee range of motion after total knee arthroplasty in the first postoperative weeks: poor recovery can be detected early," *Musculoskeletal Surgery*, vol. 103, no. 3, pp. 289–297, Dec. 2019, doi: 10.1007/s12306-019-00588-0.
- [15] M. Shamsi, M. Mirzaei, and S. S. Khabiri, "Universal goniometer and electro-goniometer intra-examiner reliability in measuring the knee range of motion during active knee extension test in patients with chronic low back pain with short hamstring muscle," *BMC Sports Science, Medicine and Rehabilitation*, vol. 11, no. 1, Dec. 2019, doi: 10.1186/s13102-019-0116-x.
- [16] R. R. Russo *et al.*, "Is digital photography an accurate and precise method for measuring range of motion of the hip and knee?" *Journal of Experimental Orthopaedics*, vol. 4, no. 1, p. 29, Dec. 2017, doi: 10.1186/s40634-017-0103-7.
- [17] N. Shah, C. Grunberg, and Z. Hussain, "Can a patient use an app at home to measure knee range of motion? utilizing a mobile app, curvate, to improve access and adherence to knee range of motion measurements," *International Journal of Sports Physical Therapy*, vol. 17, no. 3, Apr. 2022, doi: 10.26603/001c.33043.
- [18] C. Dewar *et al.*, "EMG activity with use of a hands-free single crutch vs a knee scooter," *Foot & Ankle Orthopaedics*, vol. 6, no. 4, Oct. 2021, doi: 10.1177/247301142111060054.
- [19] M. Lyu, W.-H. Chen, X. Ding, J. Wang, Z. Pei, and B. Zhang, "Development of an EMG-controlled knee exoskeleton to assist home rehabilitation in a game context," *Frontiers in Neurorobotics*, vol. 13, Aug. 2019, doi: 10.3389/fnbot.2019.00067.
- [20] S. F. del Toro, S. Santos-Cuadros, E. Olmeda, C. Álvarez-Caldas, V. Díaz, and J. L. San Román, "Is the use of a low-cost sEMG sensor valid to measure muscle fatigue?" *Sensors*, vol. 19, no. 14, p. 3204, Jul. 2019, doi: 10.3390/s19143204.
- [21] Y.-X. Liu, L. Zhang, R. Wang, C. Smith, and E. M. Gutierrez-Farewik, "Weight distribution of a knee exoskeleton influences muscle activities during movements," *IEEE Access*, vol. 9, pp. 91614–91624, 2021, doi: 10.1109/ACCESS.2021.3091649.
- [22] M. Igari *et al.*, "Development of a method for measuring joint torque using an isokinetic machine," *Japanese Journal of Comprehensive Rehabilitation Science*, vol. 5, pp. 141–146, 2014, doi: 10.11336/jjcrs.5.141.




- [23] J. Son, S. Kim, S. Ahn, J. Ryu, S. Hwang, and Y. Kim, "Determination of the dynamic knee joint range of motion during leg extension exercise using an EMG-driven model," *International Journal of Precision Engineering and Manufacturing*, vol. 13, no. 1, pp. 117–123, Jan. 2012, doi: 10.1007/s12541-012-0016-4.
- [24] B. A. Alkner, P. A. Tesch, and H. E. Berg, "Quadriceps EMG/force relationship in knee extension and leg press," *Medicine and Science in Sports and Exercise*, vol. 32, no. 2, Feb. 2000, doi: 10.1097/00005768-200002000-00030.
- [25] M. D. Jakobsen *et al.*, "Muscle activity during knee-extension strengthening exercise performed with elastic tubing and isotonic resistance," *International Journal of Sports Physical Therapy*, vol. 7, no. 6, 2012.
- [26] K. Sengchuai *et al.*, "Development of a real-time knee extension monitoring and rehabilitation system: range of motion and surface EMG measurement and evaluation," *Healthcare*, vol. 10, no. 12, Dec. 2022, doi: 10.3390/healthcare10122544.
- [27] H. Wang, S. He, J. Yu, L. Wang, and T. Liu, "Research and implementation of vehicle target detection and information recognition technology based on NI myRIO," *Sensors*, vol. 20, no. 6, Mar. 2020, doi: 10.3390/s20061765.

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