Improved Prosthetic Hand Control with Synchronous Use of Voice Recognition and Inertial Measurements

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Abstract: Voice control is one of the easiest means of interacting with machines, as no extra effort is required to generate a control signal. In addition, voice control is more intuitive than other control methods. Many studies use voice recognition to control medical devices and hand prostheses in real-time, but its use has some limitations. Furthermore, some studies take advantage of inertial measurement of the body organ to control the hand prostheses. By reviewing the advantages and limitations for each control method faces, a new synchronised control system proposed, that combines voice recognition and inertial measurement based on three combination strategies to render the prosthetic hand more dexterous, feasible, and easy to use. Five participants tested the control system based on the combination strategies to perform simple and complex prosthetic hand movements. The results showed that voice recognition had about 99% accuracy and rapid response time. Moreover, the inertial measurement control system improved the accuracy of the system, increased the degrees of freedom, and made the use of the prosthetic hand easier and more feasible.

1. Introduction
The prosthetic hand needs a high-level control system to be dexterous and to be able to perform a certain number of movements. Often, these systems are complex, costly, and the user requires long practice to use it facilely. For most of the techniques used, the user must have a long recovery period to adapt to the prosthetic hand.

Some control methods are based on biological signals of the residual limb, e.g., Electromyography (EMG) signal [1] and Mechanomyography (MMG) signal [2]. Other control methods use the mechanical signals (Force-myography, FMG) extracted from the muscles of the residual limb, such as Force-sensitive Resistors (FSR) [3], capacitive sensors [4], and ultrasonic technology [5]. Some amputees cannot use these techniques because of the condition of the residual limb or in the case of high-level amputation; in addition, it is difficult to reinstall sensors in the same place during periodic use. There are other control systems that are suitable for most amputation levels and do not depend on biological signals from the residual limb, e.g., voice control [6], inertial control [7], and Electroencephalography (EEG) [8]. Every control method has its advantages and limitations. The most common hand prostheses control technique is based on EMG signals, but it lacks classification robustness and faces the problem of synchronising of a large number of EMG electrodes; EMG signals are also difficult to detect and require an expensive processing system; in addition, it is greatly affected by noise [9]. These limitations have spurred prostheses control system designers to take on the challenge and design hybrid control methods: Fang et al. [10] merged an EMG control system with a
voice control system; Krasoulis et al. [9] improved the EMG control signal by combining it with Inertial Measurement (IM) signals. Voice Recognition (VR) control is an easy method for interacting with a machine and for controlling it in real-time. The Speaker-dependent (SD) system can pair with one user, as the last person who practised with it is the only person who can use it, and the system cannot recognize another voice until it is trained to do so [11]. Voice control is also used in many daily activities of living in some medical fields [12]. Currently, VR systems are used to control prosthetic hands in real-time [11,13–16]. However, the designed control systems have a limited number of active voice commands, leading to limited Degrees of Freedom (DOF) on the prosthetic hand.

The remote foot controller is used to control prostheses; this approach presents the possibility of controlling the prostheses effectively, and it is suitable for most amputation levels (supposing the upper limb amputee has a normal foot), especially patients with full digit amputation. FSR, capacitor sensors, or strain gauges are used to extract control signals from the foot. These sensors are placed in an insole inside a shoe worn by the user [17,18]. The control signal is generated when the user presses one of these sensors with their toes, heels, or both. Another data acquisition technique used in foot controllers is through Inertial Measurement Units (IMU). The Defense Advanced Research Project Agency (DARPA) pushed the use of IMU forward in the DEKA arm project [7].

Asyali et al. [11], Gundogdu et al. [6], Mainardi et al. [16], and Samant et al. [13] built VR control systems and applied it to prosthetic hands to perform movements. Resnik et al. [18], Navaraj et al. [17], Carrozza et al. [19], and Abdi et al. [20] used a foot control to move a prosthetic hand. From these previous studies, it is noted that the voice control lacked effective voice commands that can be used to move the hand prostheses. However, the result obtained from foot control could perform simple movements only. Moreover, in the base of our knowledge, there is no study have attempted to combine voice control with foot control to move an upper prosthetic hand yet.

In the present study, a novel hybrid control method was proposed based on a combination of VR and IM signal to manage an upper prosthetic hand in real-time to fulfilment feasible control system providing many movements and suitable for all levels of upper limb amputation. The results were promising were three different combination strategies were implemented to get more than 98% accuracy. Moreover, the hybrid system gives more space for amputees to make the most of the prosthesis by increasing the number of movements to 28 movements ranging from simple to complex actions.

2. Material and Methods
The proposed control system consists of two parts: an Elechouse VR v3.1 sensor with ordinary air microphone headset and microcontroller, foot controller consisting of an ADXL335 analogue accelerometer, Arduino Pro Mini microcontroller, HC-05 Bluetooth device, and Lithium-ion (Li-ion) battery with a charger. The proposed system works sequentially or concurrently according to the used strategies used (Section 2.5). Figure 1 shows the schematic diagram of the proposed system.

The voice wave passes through multi-processing stages in order to obtain its features. The initial step is the sampling process to convert the analog signal to train of pulses, each pulse representing the intensity of the voice during the specific time. Since the input signal is essentially human voice, the sampling frequency rate is usually set to 8 kHz [21]. The designed VR system is adopting the MFCC for the extraction voice characteristics [22]. Equation (1) is in direct relation between the energy of the voice and it can be adopted for the estimation of the energy.

\[
C(mel) = \sum_{k=1}^{K_m} c_k \cos \left( 2\pi k \frac{mel}{\theta_m} \right)
\]
where \( B_m \) is the BW analysed in Mel-domain, and \( K_m = 20 \) is a typical value assumed. \( c_k \) is the average value in dB of the filter bank energy [22]. While mel can be calculated according to Equation (2) the Mel scale, which is linear up to 1 kHz and logarithmic thereafter:

\[
mel(f) = \begin{cases} 
    f & \text{if } f \leq 1 \text{kHz} \\
    2595 \log \left(1 + \frac{f}{7000}\right) & \text{if } f > 1 \text{kHz}
\end{cases}
\] (2)

Also adopting the GMM for the statistical analysis of the data collected for the comparison [23], Equation (3). The GMM is defined as the sum of voice weighted M components:

\[
p(x|\lambda) = \sum_{i=1}^{M} b_i pi(x)
\] (3)

where \( bi \) is the weight of the mixture, \( pi(x) \) is the probability density function (pdf) of the \( i^{th} \) component with the vector \( (x) \) whose length is \( \lambda \), and \( M \) is the number of components.

The VR module utilises a similarity test, where the result that can be true if it is higher than a decision threshold, and false otherwise. While Time-Domain (TD) feature was used to extract accelerometer signal features, ADXL335 signal features were extracted from the raw tri-accelerometer data using a window size of 256 with 50% overlapping between consecutive windows. Feature extraction has demonstrated success in previous work [24]. At a sampling frequency of 200 Hz, each window represents data for 1.28 seconds. The periodicity in the data is calculated in the time domain.

2.1. Voice Recognition Control System Components

The Elechouse SD VR sensor v3.1 recognises human voice signals used to drive a prosthetic hand. It is compact, easy to use, and can provide recognition rate approaching 99% under ideal conditions, and it can integrate with different types of microcontrollers via Serial Peripheral Interference (SPI).

The Arduino Nano microcontroller, based on ATmega328p, was used to drive the prostheses directly from the VR sensor and provide wireless communication to control the prosthetic hand remotely by the foot controller.

2.2. Foot Control System Components

The ADXL335 is a three-axis acceleration measurement sensor used to record the IM of the foot. It has a minimum measurement range of ±3 g, operates on 3.7 V, and has a current drain of 350 μA.

The accelerometer sensor is connected to the microcontroller via an analogue input port. Arduino Pro Mini microcontroller based on ATmega328P was used to analyse and process the accelerometer data. The processed signals are sent wirelessly using the HC-05 Bluetooth device, which performed network

![Figure 1. Schematic diagram of the voice and foot control system.](image-url)
communication between the foot controller and upper prosthetic hand. All electronic devices used with the foot controller were fed with a 3.7 V Li-ion battery of 2000 mA/h at a discharge rate of 25 C. The battery can be extended without recharging for about 11 hours and can be recharged through a compact charger when required. Figure 2 shows the controller design.

Figure 2. The proposed foot controller unit design.

2.3. Novel Hybrid Controller for the Prosthetic Hand
The proposed VR system can provide seven DOF to the prosthetic hand. The VR unit is attached directly to the hand microcontroller based on the SPI protocol at a specific baud rate. In this work, the Bluetooth device was integrated with the hand microcontroller based on the SPI communication protocol with a specific baud rate, and Bluetooth communication parameters were set to establish a secure connection between the foot controller and prosthetic hand microcontroller. Moreover, the foot controller uses four signals to control the prosthetic hand remotely based on IM principles and sends the processed control signal via Bluetooth.

The voice and foot controllers are designed to operate together in real-time. Figure 3 shows the operation flowchart of the proposed systems. The control systems were designed to fuse the two signals [10] within three strategies so that it would be possible to use each control system on its own or to use the two systems together, depending on the user’s desire. When the two systems are operating together, one will complement the other according to the control strategy used.

2.4. Prosthetic Hand Prototype
The HANDi (Humanoid, Anthropometric, Naturally Dexterous Intelligent) hand used in this study is an intrinsic, compatible, and sensing prosthetic hand [25]. Besides the VR sensor and microcontroller, the prototype is Bluetooth-enhanced for secure remote wireless communication with the foot controller.

Figure 3. The voice and foot control signals flow chart.

2.5. Hybrid System Control Strategies
The multi-functional 3D-printed hand with six DOF used in the present study can perform simple and complex jobs in addition to performing a sequence of movements at the same time. The prosthetic hand
functions are divided into specific modes, with each mode providing some movements to meet the user’s needs. A three-strategy approach was suggested to merge voice signals with foot control signals and to use them to control the prosthetic hand. Strategy 1 and Strategy 2 have synchronous actions between VR and foot controller, while the control methods in Strategy 3 act concurrently:

- **Strategy 1:** Uses voice signals to switch between modes and uses foot control signals to activate the target movement (Figure 4a).
- **Strategy 2:** Uses foot control signals to determine the motion classes and uses voice signals to achieve the target movement (Figure 4b).
- **Strategy 3:** The voice and foot controllers work concurrently with specific actions for each controller. For example, if the command from the foot controller instructs the hand to close, it is possible to use a voice command to open it, and vice versa (Figure 4c).

In the present study, priority was given to the foot controller, and it can be switched to the voice controller according to the user’s desire. For comparison, each control method was examined individually, and then the system accuracy rate and time consumption per strategy were recorded.

![Figure 4. Strategies control signal flow. (a) Strategy 1, (b) strategy 2, and (c) strategy 3.](image-url)
3. Installation and Experimental Setup
All experiments were performed in a quiet office environment with background noise intensity of about 28–36 dB, measured using a Samsung Galaxy S5 LTE and based on a sound meter application from Google Play.

3.1. Voice Recognition Procedure
The voice control system can be activated in two stages. The first stage involves training the VR unit, and the second stage involves issuing voice commands. The VR system should be trained by the last user before it is used to control the prosthetic hand. The voice sensor used here allows training of seven channels at once. Training can be achieved by a sequence of actions: 1) connecting the VR unit to the microcontroller, 2) accessing the Arduino integrated development environment serial monitor window on a personal computer, 3) setting the baud rate at 115200 Bit Per Second (bps), 4) typing a “train” command and selecting the targeted registers to save the voice. To train the VR unit, the user is required to repeat each voice command twice and for all voice commands. Upon completion of the training phase, seven stored voice commands are ready to be called on to perform seven movements by the prosthetic hand. Next, the system is put in recognition mode, where the required prosthetic hand functions can be achieved by pronouncing the voice command.

3.2. Foot Control Procedure
The foot controller is operated based on the principle of the IM of the user’s foot. An analogue accelerometer is worn on the ankle to detect the foot orientation and sends three signals representing the position on the main axes, i.e., X, Y, and Z. Four control signals can be obtained by tilting the foot (forward, backward, right, left). The foot controller threshold value was set and adjusted for each orientation; moreover, the neutral position was selected and set to determine the signal limits of each movement. The position signals are processed, analysed, and encoded by the Arduino Pro Mini microcontroller. The X, Y, and Z direction signals are received and merged to process together using auto-correlation in time domain as following in Equation (4) [26], [27].

\[ S2 = Corr(S1, z) = \frac{Cov(S1, z)}{\sigma^{S1} \sigma^z} \quad \text{and} \quad S1 = Corr(x, y) = \frac{Cov(x, y)}{\sigma^x \sigma^y} \]  

(4)

where: cov: is a measure of the joint variability of two random variables, \( \sigma^x \): is the standard deviation of \( x \), \( \sigma^y \): is the standard deviation of \( y \), \( \sigma^z \): is the standard deviation of \( z \), \( \sigma^{S1} \): is the standard deviation of \( S1 \).

The control signals are sent as 1-byte American Standard Code for Information Interchange (ASCII) code to the prosthetic hand via Bluetooth. Then, the prosthetic hand microcontroller will receive the signal via Bluetooth and decode it to perform the required movement by the prosthetic hand.

3.3. Participant Preparation
Five volunteers (four men and one woman; age, 31–68 years) attended a tutorial on how the experiment worked, the activity required, and how the voice control system was to be trained and used. In addition, the participants were instructed on how the foot controller was to be attached to the foot ankle and used. The participants were asked to put on the microphone headset and adjust the position of microphone to 5–10 cm from the lips; this distance is best for capturing sound and extracting its characteristics [28]. Then, each participant issued training voice commands (Section 3.1) and adjusted the four threshold points as well as the neutral point (Section 3.2). To investigate the result reproducibility of the proposed system, the participants repeated each voice command 10 times for seven commands and used the foot controller to produce 70 trials. This procedure was repeated with every strategy and the accuracy for each was recorded. Figure 6 shows the participants’ preparation for
the experiment. Any spoken word from pre-stored words in training mode could be used as a command. The seven commands chosen were single-syllable words in English. Moreover, the foot controller was adjusted to discrimination tilting in four directions. The prosthetic hand received the control signals directly from the VR unit and remotely from the foot controller via Bluetooth at a baud rate of 38200 bps.

3.4. Control Strategies
System accuracy and time was taken to complete different movements was examined using three strategies for controlling the prosthetic hand in real-time:

- **Strategy 1:** The VR signals works as the mode selector for achieving seven modes, each with four movements from the foot-based controller. The result is 28 active control signals.

- **Strategy 2:** The foot controller acts as the mode selector, wherein this case the four modes available each has active seven voice commands. This strategy provides 28 DOF to the prosthetic hand.

- **Strategy 3:** The foot controller and VR control signals work concurrently to achieve 11 different movements: seven achieved via the voice controller and four achieved via the foot controller.

3.5. Measurements and Performance Evaluations
The preparation time for participants to put on and adjust the foot controller and to put on the microphone headset and train the voice controller was approximately 320 seconds per user. Taking into consideration the fact that the participants had used the VR system previously. Figure 6 shows the system recognition rate for the 210 voice commands issued by each participant in this experiment to test the three combinations strategies. Figure 7 shows changes in the foot control signal whenever the participant's foot is moved in any direction, and the 3-channel signals were analysed to specify the target movement. Voice system recognition rate commands and foot controller accuracy are visually recorded by calculating the number of correct hand movements to the target movements and the number of failures. An accuracy equation [29][30] was adopted to calculate the recognition rate and foot controller accuracy, as in Equation (5). Also, the Standard Deviation (STD) [29] was calculated based on the following Equation (6)

\[
\text{Accuracy} \ (\%) = \frac{\text{no.of correct attempt}}{\text{total no.of attempts}} \times 100 \quad (5)
\]

\[
STD = \sqrt{\frac{\sum_{i=1}^{m} (x_i-x)^2}{m-1}} \quad (6)
\]
where $x_i$ is the mean of input data $x$, and $m$ is the number on data sequence.

![Figure 6](image)

**Figure 6.** System recognition rate for voice commands from participants for the three proposed strategies.

![Figure 7](image)

**Figure 7.** Foot controller X-, Y-, and Z-axis signals, where each change in the signal pattern indicates a change in the orientation of the foot in the following sequence: neutral, forward, neutral, backward, neutral, right, neutral, left, neutral.

### 4. Results and Discussion

Table 1 shows the system accuracy of the five participants for performing the movements for each strategy. The prosthetic hand response to the foot controller and VR signals was visually recorded for eight movements performed by each participant for each strategy (Section 3.4).

| Subject | Strategy 1 accuracy (%) | Strategy 2 accuracy (%) | Strategy 3 accuracy (%) |
|---------|-------------------------|-------------------------|-------------------------|
|         | Foott signal            | Voice signal            | Foott signal            | Voice signal | Foott signal | Voice signal |
| P1      | 98.6                    | 98.6                    | 98.1                    | 97.1         |              |              |
| P2      | 98.6                    | 98.6                    | 98.6                    |              | 98.6         |              |
| P3      | 100                     | 95.7                    | 100                     | 98.6         | 100          | 98.6         |
| P4      | 97.1                    | 98.6                    | 97.1                    |              | 97.1         |              |
| P5      | 98.6                    | 97.1                    | 98.6                    |              | 98.6         |              |
| Average | 100                     | 97.7                    | 100                     | 98.3         | 100          | 98.0         |

|         | 98.6                    | 99.2                    | 99.0                     |

$P^*$ = Participant ID
Table 2 shows the average time taken for the prosthetic hand to evaluate the different movements for each strategy used. A stopwatch was used to record the time taken by the prosthetic hand to perform a full movement based on the foot and voice controller signals.

| Subject | Strategy 1 (ms) | Strategy 2 (ms) | Strategy 3 (ms) |
|---------|----------------|----------------|----------------|
| P1      | 920            | 760            | 840            |
| P2      | 840            | 680            | 710            |
| P3      | 810            | 590            | 760            |
| P4      | 790            | 690            | 710            |
| P5      | 860            | 620            | 690            |
| Average | 844            | 668            | 742            |

The prosthetic hand response to foot controller signals was ideal; the result showed 100% correct response to four completely different movements, whereas the best recognition rate for the voice system was 98.3% as shown in Table 1. Clearly, participant P1 had the longest response time because he has a sciatic nerve problem, and his ankle does not move as freely as that of a person without a sciatic nerve problem. To evaluate the strategies used in the present study and to discuss the results, the system’s accuracy, time was taken to perform a movement, and the number of movements provided by each strategy should be taken in consideration. Figure 8 shows the time response for each strategy with a STD error bars based on Equation (6).

- **Strategy 1**: Table 1 clearly shows that the average system accuracy was 98.6%. Moreover, Table 2 and Figure 9 show that the average time taken by the system to perform a movement was 844 ms (STD 50.5 ms), which is a high deviation compared to the other strategies. Here, seven available modes can select by voice; each mode has four different movements delivered by the foot controller. The time response, in this case, was the longest, as this strategy uses the foot controller to perform the target movement, and the foot controller response time was clearly little bit slower than that of voice control. This strategy is suitable for an amputee who has to use several modes in their daily life.

- **Strategy 2**: It provides four mode sets that can be selected using the foot controller. Every mode has seven voice commands to execute seven movements. The average system accuracy was 99.2% (Table 1), and the participants used an average of 668 ms to perform a movement with the prosthetic hand (Table 2). Figure 8 shows that the STD for time is clearly 66.2 ms, and it is lowest response time if compared with the other strategies. This strategy is suitable
for an amputee who needs limited modes set with several functions per mode. For example, a full-digit amputee can use the foot controller for joint activations, where the shoulder, elbow, wrist, and palm can be set as modes that can be selected by tilting the foot. When any mode is activated, the user’s voice is used to perform seven movements on the prosthetic hand.

- **Strategy 3:** The foot controller works in parallel with the VR controller. The average system accuracy was 99.0%, and the average time taken to perform a movement was 742 ms (STD 60.6 ms) (Table 1, Table 2, and Figure 8, respectively). This strategy prepares 11 movements and is suitable for an amputee who does not require many movements. The amputee can set the foot controller to perform the most used functions (e.g., open, close, pinch, tripod) [31] and use the VR controller for more specific functions.

The control of hand prostheses by voice is a modern technique, so it is not expected to find a large number of researches have control system with this technology. The comparison based on factors that have a direct impact on the control system and its quality and the possibility of practical use in the management of hand prostheses Table 3 shows the competition between this work and similar works in literature based on recognition techniques used to control prosthetic hand, operation state, recognition rate, number of active voice command, and language supported by the system. In addition, through extensive research in the previous literature found very few uses the inertia signal in the process of controlling the hand prostheses. Also, in the base of our knowledge, this is the first study that combines VR and foot control system. Table 4 shows the comparison between previous works and this works for foot-based control system.

### Table 3. Voice-based control system results for similar previous work.

| Ref. | Recognition technique used | Operation state | Recognition rate (%) | No. of active voice commands | Language |
|------|---------------------------|-----------------|----------------------|-----------------------------|----------|
| [14] | Speech recognition        | Internet-based  | NA                   | 5                           | English  |
| [16] | Voice recognition         | Stand-alone     | 97                   | 3                           | Italian  |
| [11] | Voice recognition         | Stand-alone     | NA                   | 2                           | English  |
| [6]  | Voice recognition         | Stand-alone     | 90                   | 6                           | English  |
| [13] | Voice recognition         | Stand-alone     | 88.3                 | 5                           | English  |
| **This study** | Voice recognition    | Stand-alone     | 98.0                 | 7                           | English  |

### Table 4. Comparison between foot-based control system results available in the literature and this study.

| Ref. | Sensor type                  | Sensor location | Data transition       | Accuracy (%) | No. of movements |
|------|------------------------------|-----------------|-----------------------|--------------|------------------|
| [18] | Gyroscope + accelerometer + magnetometer | Ankle or instep | Wired & Wireless | NA           | 16               |
| [19] | Accelerometer + FSR         | Insole          | Wireless              | NA           | 5                |
| **This study** | Accelerometer | Ankle           | Wireless              | 100          | 4                |
5. Conclusion

In multifunctional prosthetic hand control, the problem of insufficient control signals and other limitations [9] might be resolved by a feasible hybrid real-time control system for achieving an easy-to-use additional movement control system for a prosthetic hand. A practical test in intact-bodied volunteers demonstrated that the foot control system successfully promotes the VR control system to reach 99.2% of accuracy. Also, improves the control feasibility and increases the number of active commands to achieve 28 movements.

Here, three linking strategies were investigated by changing the combinations between the foot control and VR control signals. Each strategy has its own benefits, but Strategy 2 appears more feasible and is a suitable solution for many amputees as well, as it has 99.2% accuracy and rapid response time than the other strategies, as well as being easier to use than Strategy 1. While strategy 3 is the most practical strategy but it performs 11 movements only with 99.0% of accuracy.

The future plan is; test the control systems on amputees, increase the number of voice commands, and develop the foot controller to enhance the number of active movements.

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References

[1] Micera S, Carpaneto J and Raspopovic S 2010 Control of hand prosthesis using peripheral information IEEE Rev inBiomedical Eng 3 48–68
[2] Silva J, Heim W and Chau T 2004 MMG-based classification of muscle activity for prosthesis control Proc 26th Annu Int Conf IEEE Eng Med Biol 968–71
[3] Cho E, Chen R, Merhi L-K, Xiao Z, Pousett B and Menon C 2016 Force Myography to Control Robotic Upper Extremity Prostheses: A Feasibility Study Front Bioeng Biotechnol 4 1–12
[4] Roland T, Amüss S, Russold M F, Wolf C and Baumgartner W 2016 Capacitive Sensing of Surface EMG for Upper Limb Prostheses Control 30th Eurosensors Conf EUROSENSORS 2016, Procedia Eng 168 155–8
[5] Sikdar S, Rangwala H, Eastlake E B, Hunt I A, Nelson A J, Devanathan J, Shin A and Pancrazio J J 2014 Novel method for predicting dexterous individual finger movements by imaging muscle activity using a wearable ultrasonic system IEEE Trans Neural Syst Rehabil Eng 22 69–76
[6] Gundogdu K, Bayrakdar S and Yucedag I 2018 Developing and modeling of voice control system for prosthetic robot arm in medical systems J King Saud Univ - Comput Inf Sci 30 198–205
[7] Resnik L, Klinger S L and Etter K 2014 The DEKA Arm: Its features, functionality, and evolution during the veterans affairs study to optimize the DEKA Arm Prosthet Orthot Int 38 492–504
[8] Beyrouthy T, Al Kork S K, Kobane J A and Abdulmonem A 2016 EEG Mind controlled Smart Prosthetic Arm 2016 IEEE Int Conf Emerg Technol Innov Bus Pract Transform Soc EmergiTech 2016 404–9
[9] Krasoulis A 2017 Improved prosthetic hand control with concurrent use of myoelectric and inertial measurements J Neuroeng Rehabil 71 1–14
[10] Fang P, Geng Y, Wei Z, Zhou P, Tian L and Li G 2015 New Control Strategies for Multifunctional Prostheses that Combine Electromyographic and Speech Signals IEEE Intell Syst 30 47–53
[11] Asyali M H, Yilmaz M, Tokmakçi M, Sedef K, Aksebzeci B H and Mittal R 2011 Design and implementation of a voice-controlled prosthetic hand Turkish J Electr Eng Comput Sci 19 33–46
[12] Zinchenko K, Wu C Y and Song K T 2017 A study on speech recognition control for a surgical robot IEEE Trans Ind Informatics 13 607–15
[13] Samant P and Agarwal R 2015 Real-time speech recognition system for prosthetic arm control Int J Sensing, Comput Control 5 39–46
[14] Ujwal R, Narun R, Surana H, S N S and Dheeraj C P 2018 Voice Control Based Prosthetic Human Arm Int Res J Eng Technol 5 473–7
[15] Gruppioni E, Salutti B G, Cutti A G, E M and Davalli A 2008 a Voice-Controlled Prosthesis: Test of a Vocabulary and Development of the Prototype Proceeding MEC (Myoelectric Control Conf
[16] Mainardi E and Davalli A 2007 Controlling a prosthetic arm with a throat microphone Proc 29th Annu Int Conf IEEE Eng Med Biol 3035–9
[17] Navaraj W T, Heidari H, Polishchuk A, Shakhthivel D, Bhatia D and Dahiy A R 2015 Upper limb prosthetic control using toe gesture sensors 2015 IEEE SENSORS 1–4
[18] Resnik L, Klinger S L, Etter K and Fantini C 2014 Controlling a multi-degree of freedom upper limb prosthesis using foot controls: User experience Disabil Rehabil Assist Technol 9 318–29
[19] Carrozza M C, Persichetti A, Laschi C, Vecchi F, Lazzarini R, Tamburrelli V, Vacalebri P and Dario P 2005 A novel wearable interface for robotic hand prostheses Proc 2005 IEEE 9th Int Conf Rehabil Robot 109–12
[20] Abdi E, Burdet E, Bouri M and Bleuler H 2015 Control of a supernumerary robotic hand by foot: An experimental study in virtual reality PLoS One 10 1–14
[21] Pernet C R, McAleer P, Latinus M, Gorgolewski K J, Charest I, Bestelmeyer P E G, Watson R H, Fleming D, Crabb F, Valdes-Sosa M and Belin P 2015 The human voice areas: Spatial organization and inter-individual variability in temporal and extra-temporal cortices Neuroimage 119 164–74
[22] Maesa A, Garzia F, Scarpiniti M and Cusani R 2012 Text Independent Automatic Speaker Recognition System Using Mel-Frequency Cepstrum Coefficient and Gaussian Mixture Models J Inf Secur 03 335–40
[23] Van K N, Minh T P, B T N S, B M H L, Dang T T and Dinh A 2017 Text-dependent Speaker Recognition System Based on Speaking Frequency Characteristics vol 10646 (Springer International Publishing)
[24] Bremznes T, Gorricho J L and Cotrina J 2009 Activity recognition from accelerometer data on a mobile phone Lect Notes Comput Sci (including Subser Lect Notes Artif Intell Lect Notes Bioinformatics) 5518 LNCS 796–9
[25] Brenneis D J A, Dawson M R and Pilarski P M 2017 Development of the Handi Hand: an Inexpensive, Multi-Articulating , Sensorized Hand for Machine Learning Research in Myoelectric Control Myoelectric Control Up Limb Prosthetics Sympt 15–8
[26] Pan G, Li S and Zhu Y 2019 A Time – Frequency Correlation Analysis Method of Time Series Decomposition Derived from Synchronized S Transform Appl Sci 9 1–17
[27] Rodgers J L and Nicewander W A 1988 Thirteen Ways to Look at the Correlation Coefficient Am Stat Assoc 42 59–66
[28] Mittal Y, Toshniwal P, Sharma S, Singhal D, Gupta R and Mittal V K 2016 A voice-controlled multi-functional Smart Home Automation System 12th IEEE Int Conf Electron Energy, Environ Commun Control (E3-C3), INDICON 2015 1–6
[29] Chan T F and Lewis J G 1979 Computing Standard Deviations: Accuracy Commun ACM 22 526–31
[30] Too J, Abdullah A R, Saad N M and Tee W 2019 EMG feature selection and classification using a Pbest-guide binary particle swarm optimization Computation 7
[31] Al-Timemy A H, Bugmann G and Escudero J 2018 Adaptive Windowing Framework for Surface Electromyogram-Based Pattern Recognition System for Transradial Amputees Sensors (Basel) 18 1–15.