Recent Innovations in Electromyography for Biomedical Applications: A Systematic Literature Review

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***Abstract*— In recent years, extended efforts have been made to develop innovative applications for electromyography on the human body. Yet, there is a dearth of literature synthesizing these types of innovative medical applications. A systematic literature review was conducted to investigate the most recent initiatives undertaken in the field of electromyography. Four databases, including PubMed, ScienceDirect, Web of Science, and Proquest were searched for the relevant studies pertaining to the research topic. Only peer reviewed, scholarly journal articles published in English between 2016 and May of 2017 and with full text available were included. Such inclusion and exclusion criteria yielded a total of 13 studies for the final synthesis. An inductive analysis of these studies revealed some common themes, namely the three key areas of innovation: electromyography based wearables to address a solution to a problem, electromyography based wearables to control prosthetic hands, and electromyography signals used as medical tools.**

I. INTRODUCTION

The field of electromyography is a study of the electronic instruments which are used to measure the energy of muscles and the analysis of the data obtained [1]. Electromyography (EMG) is an important technique which enables the diagnosis of neuromuscular disorders, as well as the investigation of human movement and neuromuscular physiology [2]. The equipment used in electromyography is known as an electromyograph and the signal produced is referred to as an electromyogram.

Skeletal muscles, which act as motors in the human body to enable movement, generate electromyogram signal [3]. These signals represent the electric potential field produced when the outer muscle fiber membranes in the muscle depolarize due to the electrical activity of muscle fibers when a muscle contracts [4]. Surface electrodes or intramuscular electrodes can be utilized for detecting these signals [4]. The tissues which separate the source of the signal and the electrodes behave as a volume conductor, and it is the property of these tissues which eventually determines the properties of the electromyogram signals ultimately collected and analyzed [4].

Electromyography offers many advantages, since it is a non-invasive, safe, and easy method for objectively quantifying the energy of muscles [1]. This method enables both the observation of muscle energy as it changes continuously with movement as well as when the muscle is at rest [1]. Electromyography has the potential for many applications, including rehabilitation, sports training, treatment planning, and research [1]. Electromyography is widely applied for muscle assessment, and in fact, Bareket and colleagues note that electromyography is commonly used for mapping muscle activation [5].

However, in recent years, many studies have been conducted to develop a variety of innovations for electromyography on the human body for biomedical applications. According to Frankelius, innovation is a concept that possesses a high level of originality and is new and revolutionary [6]. For example, Khan recently reported the development of novel dry electrodes for long term electromyography recordings by Bareket and colleagues [7]. These soft carbon screen-printed electrodes act as temporary tattoos to map muscle activation, and its wireless capabilities enable the user to carry out daily activities while the EMG signals are recorded [5]. Yet, there is a dearth of literature which synthesizes these types of innovative medical applications. Thus, the aim of this systematic literature review is to investigate and synthesize the most recent initiatives undertaken in the field of electromyography for innovative biomedical applications. The results from this systematic literature review will also enable the identification of gaps in research which can help to determine directions needed for future studies.

II. METHODOLOGY

This systematic literature review is focused on synthesizing the most recent initiatives and innovations in electromyography for biomedical applications. In order to systematically search for relevant articles, the following four databases were used: PubMed, ScienceDirect, Web of Science, and Proquest. PubMed was selected as a potentially relevant database, since it can access the Medline database and provides articles related to biomedical subjects. ScienceDirect was chosen, since it is a leading source and database for technical, medical, and scientific research. Web of Science was also selected as potentially relevant, as it is a comprehensive database containing literature on scientific topics and also provides access to cross-disciplinary research [8]. Lastly, ProQuest was chosen, because it functions as a multidisciplinary database granting access to a variety of subject areas.

A preliminary search on electromyography revealed that in addition to muscle activation, much of the latest research in this field pertained to facial electromyography and novel wearable electromyography sensors. Hence, these two topics were included in the keyword search terms in order to maximize the relevant articles obtained. Boolean operators were implemented to increase the sensitivity of the search. For example, a template containing search terms was constructed as follows: (“electromyography” OR “EMG”) AND (“biomedical applications”). In lieu of “biomedical applications”, the term “wearable” and the term “innovation” were also used. The keywords “facial electromyography” were also independently used as a search term. Thus, these four keyword search term queries were implemented for all four databases.

For the initial keyword search, no inclusion or exclusion criteria were specified, which resulted in a total of 11572 articles. Once these articles were obtained, filters were applied based on inclusion and exclusion criteria. Only peer reviewed, scholarly journal articles written in English and the full text of the articles available were included. Additionally, a time frame was specified in order to restrict the articles and studies to the most recent initiatives. Hence, only articles published between 2016 and 2017 were included. Once these inclusion and exclusion criteria were specified in the keyword search queries for each database, 10540 articles were excluded to result in a total of 1032 remaining articles.

The titles of these 1032 articles were then reviewed for relevance in order to ensure that the article focused on electromyography and biomedical applications related to the human body. Upon screening the titles, 913 articles were excluded and a total of 119 articles remained. At this stage, duplicate studies were also removed, which resulted in a total of 73 articles. The abstracts of these 73 articles were then screened for relevance, with only experiment based studies being included. Any study that focused on improving electromyogram signals was excluded, since these studies were not proposing any novel applications. Studies that collected EMG data purely to test a theory, investigate a phenomenon, or develop technology not related to electromyography were excluded. Additionally, the majority of the studies on facial electromyography were using EMG for applications that were psychology based. For example, many of these studies were using facial EMG in order to test psychology theories or were using facial EMG to collect the responses of humans to various stimuli for investigating phenomena in psychology or cognitive neuroscience. Thus, these studies were deemed irrelevant to the focus of this paper. Upon reading the abstracts for relevant papers, 51 studies were excluded to result in a remainder of 22 papers.

The remaining 22 papers were further investigated for relevance to the focus of this paper by reading through the full text. Any study where the manuscript was available but not yet officially published was excluded. Comparative studies, such as the comparison between electromyography and force myography, were not included. Any paper that did not focus on a biomedical application related to the human body was excluded. Additionally, any studies which focused on developing better electrodes for obtaining the EMG signals, as opposed to focusing on EMG itself, were excluded. Lastly, any studies which developed models and used EMG signals purely to verify the validity of the models were also not included. Thus, 9 more studies were excluded to result in a total of 13 studies in the final pool of articles for this systematic literature review. An overview of this literature search and screening methodology, as well as the number of articles included and excluded at each stage of the process, is outlined by Figure 1.

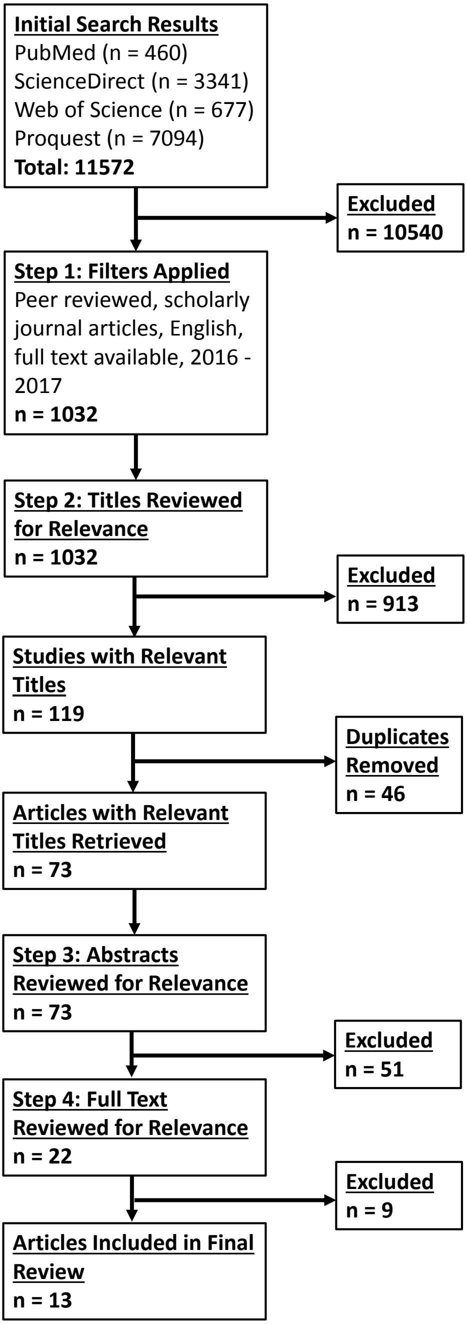

Fig. 1. Overview of the literature search and screening methodology.

III. RESULTS

The initial keyword search yielded a total of 11572 articles across all four databases. Upon applying the inclusion and exclusion criteria and screening the titles, abstracts, and full text, the number of articles relevant to the focus of this paper was dwindled down to a total of thirteen studies. These studies were conducted across many different countries spanning four continents, including one study from North America, one study from South America, nine studies from Europe, and two studies from Asia. Out of the thirteen studies on the most recent innovations for biomedical applications of electromyography, four of them were from Italy alone.

It was not possible to compare the number of selected studies conducted in 2016 and 2017, since the systematic literature review was conducted in May of 2017 and therefore it was not possible to consider studies published from June to December of 2017. However, a general trend can be observed when the number of studies published are organized by month for each year. As indicated by Figure 2, there were no studies on the innovative biomedical applications of electromyography in 2016 until the month of August, when there were three. Although the number of studies decreased after August, there were still a steady number of studies each month on this topic until the end of the year. One study was published each month for September and October, and the number of publications increased to two for both November and December. As illustrated by Figure 3, this trend seemed to continue to 2017, as one study on this topic was steadily published each month until May. However, only the month of February had no publications.

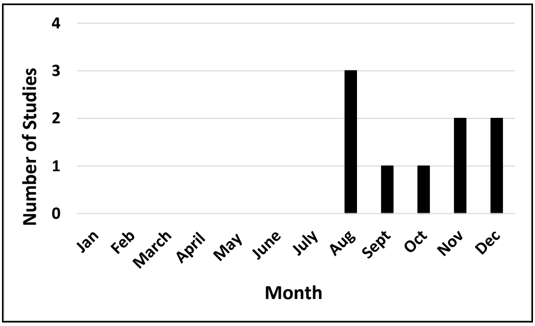

Fig. 2. Number of studies published each month in 2016 on innovations for biomedical applications of electromyography.

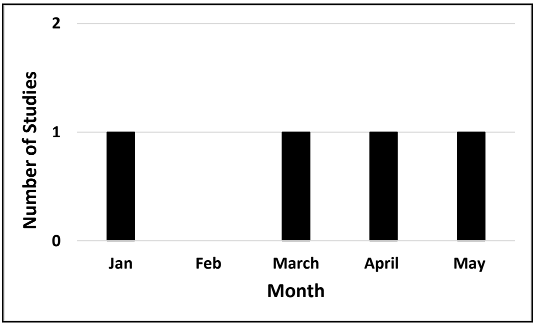

Fig. 3. Number of studies published each month in 2017 on innovations for biomedical applications of electromyography.

An inductive approach for the analysis of each of the selected studies revealed the emergence of common themes. Based on the objectives, purpose, and main findings, each study can be categorized into one of three areas for innovative biomedical applications of electromyography. For example, three of the studies developed electromyography based wearables to address a solution to a problem. A summary of the key features of these three studies is indicated by Table 1. Five studies developed electromyography based wearables in order to improve the control of prosthetic hands, and a summary of the key features is provided by Table 2. The remaining five studies focused on using electromyography signals as a medical tool. A summary of the key features of these five studies is provided by Table 3. The focus of all thirteen studies was on electromyography and the development of an innovative biomedical application using this technology.

TABLE 1. ELECTROMYOGRAPHY BASED WEARABLES TO ADDRESS A SOLUTION TO A PROBLEM.

Reference	Title	Country	Purpose	Main Findings
Golab et al. (2016)	A wearable headset for monitoring electromyography responses within spinal surgery	United Kingdom	To improve efficiency of selective dorsal rhizotomy neurosurgical spinal procedure	Developed innovative wearable information display for monitoring EMG responses during spinal surgery
Wu et al. (2016)	A wearable system for recognizing American Sign Language in real-time using IMU and surface EMG sensors	United States	To develop a low cost and efficient, wearable real-time American Sign Language recognition system	Developed a wearable real-time system for recognizing American Sign Language by fusing information from an inertial sensor and a surface EMG sensor for an average accuracy of 96.16%
Biagetti et al. (2016)	Wireless surface electromyography and electrocardiograph system on 802.15.4	Italy	To develop a low cost wireless system to monitor muscle activity during fitness	Designed a system acquiring signals from wearable nodes which can be used in combination with a smartphone application to provide a platform for monitoring muscle fitness metrics extracted from EMG and electrocardiograph signals

TABLE 2. ELECTROMYOGRAPHY BASED WEARABLES TO IMPROVE CONTROL OF PROSTHETIC HANDS.

Reference	**Title**	**Country**	**Purpose**	**Main Findings**
Hussain et al. (2016)	An EMG interface for the control of motion and compliance of a supernumerary robotic finger	Italy	To develop a novel EMG control interface to control motion and joints compliance of a supernumerary robotic finger	Designed an EMG control interface which can be used both by chronic stroke patients to compensate missing grasping abilities and by healthy subjects to increase hand dexterity
Brunelli et al. (2016)	Design considerations for wireless acquisitions of multichannel sEMG signals in prosthetic hand control	Italy	To design a body-worn system for prosthetic hand control based on surface EMG signals	Developed a wearable device for sEMG signal acquisition and recognition of performed motion for real-time control of prosthetic hands
Batzianoulis et al. (2017)	EMG-based decoding of grasp gestures in reaching-to-grasping motions	Switzerland	To develop an EMG-based learning approach to decode grasping intention at early stage of reach-to-grasp motion of prosthetic hand	Designed an EMG signal based decoding to control prosthetic device, which showed a 90% accuracy for detection of final grasp 0.5s after motion onset
Wang et al. (2017)	Real-time and wearable functional electrical stimulation system for volitional hand motor function using the electromyography bridge method	China	To develop a wearable functional electrical stimulation system for real-time volitional hand motor function control using the EMG-bridge method to improve voluntary participation of hemiplegic patients	Prototype system developed which optimized surface EMG thresholds and trained logistic regression classifier parameters for high accuracy wrist and hand motion control for suitability of rehabilitation at home
Tavakoli et al. (2017)	Single channel surface EMG control of advanced prosthetic hands: A simple, low cost and efficient approach	Portugal	To develop a simple, fast, low cost system which can recognize up to 4 gestures with a single channel surface EMG signal	Designed a low energy system which used a single channel EMG sensor to control a prosthetic hand with 90% accuracy

TABLE 3. ELECTROMYOGRAPHY SIGNALS AS A MEDICAL TOOL.

Reference	**Title**	**Country**	**Purpose**	**Main Findings**
Maneski et al. (2016)	Stimulation map for control of functional grasp based on multi-channel EMG recordings	Serbia	To develop a method using EMG to select appropriate positions of electrodes for transcutaneous muscle activation with electrical stimulation	EMG activity maps estimated from signals from nonparetic and paretic forearms revealed that areas with differences between the two EMG maps were significant and identified as stimulation sites
Eskes et al. (2017)	Predicting 3D lip movement using facial sEMG: A first step towards estimating functional and aesthetic outcome of oral cancer surgery	Netherlands	To develop a patient specific 3D lip model to improve predictions and potential functional consequences of oral cancer surgery	Results showed surface EMG signals contain enough info to control 3D dynamic models of lip movements and used to design a 3D lip model with volunteer specific surface EMG activities
Kalani et al. (2016)	Towards an sEMG-based tele-operated robot for masticatory rehabilitation	Iran	To develop a real-time trajectory generation for masticatory rehabilitation robot based on surface EMG signals	Generated masticatory motion by a robot based on sEMG signals and used to create a jaw model to demonstrate time-varying behavior of muscle lengths during rehabilitation process
Spolaor et al. (2016)	Altered EMG patterns in diabetic neuropathic and non-neuropathic patients during step ascending and descending	Italy	To investigate presence of functional alterations in diabetic subjects during stair climbing to explore relationship between altered muscle activation and temporal parameter using EMG patterns	Significant correlations between speed and timing surface EMG activity in presence and absence of neuropathy and there was early lower limb surface EMG activity detected in those who performed task faster
Politti et al. (2016)	Characteristics of EMG frequency bands in temporomandibular disorders patients	Brazil	To determine whether any specific frequency bands of sEMG signals are more susceptible to alterations in patients with temporomandibular disorders (TMD) compared to healthy subjects	Median frequency values in TMD patients significantly higher than those for healthy subjects for all muscles assessed and therefore TMD dysfunctions can be quantitatively identified by surface EMG

A. Electromyography based wearables to address a problem

Three of the thirteen studies designed electromyography based wearable devices to develop a solution to a problem that is often faced by people. Wearable technologies are defined as devices which act as electronic computers that can be worn on the body as part of a person's clothes or as an accessory, and according to Nasir and Yurder, wearable technologies play an important role in healthcare innovation [9]. Wearables can process and store data and allow real-time data exchange between a device and a network [9]. Recent advances in wearable technology has resulted in a global rise in the wearable devices market, and it is predicted that compared to the retail revenue of $1.4 billion in 2013 from wearable devices, the retail revenue will increase to $19 billion by 2018 [10].

One study developed a novel EMG response display for the Google Glass wearable headset [11]. The aim of the study was to develop this wearable technology for surgeons to use in order to enhance the efficiency of the selective dorsal rhizotomy neurosurgical procedure – a procedure which reduces the plasticity of stiff and tight muscles in the lower limbs [11]. The bones of the spine need to be opened during surgery in order to expose the sensory nerve roots, which are each tested by a probe to record the electromyography muscle electrical patterns [11]. Thus, an intraoperative neurophysiologic monitoring (IONM) display using electromyography is assessed by the surgeon to identify the most responsive nerves which would need to be cut [11]. During this procedure, the neurosurgeon would need to communicate with the neurophysiologist across the operating table to identify the most responsive sensory nerves, and Golab and colleagues stress the possibility of a lack of communication and efficiency, which may negatively impact the surgical procedure [11]. Hence, the development of this wearable headset displaying the EMG responses would allow the surgeon to directly view the EMG waveforms during the procedure without diminishing his or her attention during the surgery and without having to rely on second hand information from another party [11]. Furthermore, Golab and colleagues assert that implementing this new wearable technology may also potentially improve the IONM technique during the procedure itself, since if two surgeons were to wear the device simultaneously to view the EMG signals, then they can both provide an opinion as to which nerves were the most responsive and need to be cut [11].

A study conducted in the United States developed a wearable real-time system which fused information from an inertial sensor and a surface EMG sensor to recognize American Sign Language (ASL) [12]. This is the first device to fuse information from both sensors for application in ASL, and it can successfully recognize up to 80 commonly used ASL signs with a 96.16% average accuracy [12]. Communication barriers may exist when deaf individuals who rely on sign language, because they are unable to hear or speak, cannot communicate with hearing individuals who are unable to sign or interpret sign language [12]. Although this communication barrier can be alleviated by interpreters or text writing, these two modes of communication can be expensive, lead to loss of privacy, and may be too slow [12]. Hence, sign language recognition systems which can translate sign language into text or speech are important to address this gap in communication [13, 14]. Inertial measurement units (IMU) are often used in sign language recognition systems, since they measure angular velocities with three axis gyroscopes and measure acceleration and gravity with three axis accelerometers, which enable the sensors to capture hand and arm movements and orientations [12]. In contrast, surface EMG sensors measure the muscle electrical activity, which enable them to detect different gestures [12]. Although a similar wearable system was previously developed to recognize Chinese Sign Language back in 2012 [15], the fusion of these two modalities is particularly important for recognizing ASL. In ASL, some signs use similar arm movements, but differ in the finger and hand configurations. Thus, the addition of surface EMG sensors to IMU sensors allow the detection of the differences in these finger movements to be able to distinguish the signs, which would not have been possible with IMU sensors alone [12].

Another study developed a low cost and wireless wearable system which can extract fitness metrics from both electrocardiograph (ECG) and surface EMG signals [16]. Current wearable technologies that track fitness monitor parameters such as heartbeat, calories consumed, or the distances which are walked/run [16]. However, it is also important to monitor the strength of muscles during fitness activities, since it can indicate energy expenditures as well as provide information on whether a particular exercise is being performed correctly, and yet, little attention has been given to wearable devices which can monitor muscle activities during fitness [17]. Thus, the development of this wearable system for acquiring muscle fitness metrics is particularly important, as the information it can provide to the user may indicate muscle stimulation or fatigue during a workout. The design of this wearable system is also innovative, because it can acquire both surface EMG and ECG signals with a software-selectable bandwidth [16]. Devices which are typically used to record EMG and ECG signals are different, since the useful bandwidth to acquire EMG signals need to be above 500 Hz, while in contrast the useful bandwidth for ECG signals need to be below 100 Hz [18]. However, flexibility was conferred in the design of this system without increasing its cost to enable the same signal chain to be used for both ECG and surface EMG signal acquisition [16].

B. Electromyography based wearables to control prosthetics

Five of the thirteen studies developed electromyography based wearable technology to improve prosthetics, and in particular, all of these studies were concerned with improving the control of prosthetic hands. Surface EMG (sEMG) as a sensing technology enables the detection of electrical potentials and activities generated by muscle contractions and therefore can recognize movements that are performed [19]. In all five of these selected studies, sEMG signals were used to recognize the hand and arm movements, since sEMG signals processed by computational algorithms enable intentional movements to control the prosthetic devices [19].

In one study, Batzianoulis and colleagues developed a sEMG-based learning approach which can decode the grasping intention of a prosthetic hand before the final hand preshape or grasp occurs [20]. Systems slow to respond are often inconvenient, which may discourage some individuals from using a prosthetic device [21]. It has also been reported that comfort is one of the priorities when stroke and amputee patients choose a prosthetic device [21, 22]. Therefore, prosthetic devices ought to be able to detect human intention early, as an accurate estimation of the final grasp posture would ensure the prosthetic device reacts fast enough for a natural transition from the reaching to the grasping phase [20]. The results from this sEMG-based decoding approach showed a 90% accuracy in detecting the final grasp postures approximately 0.5 seconds after the motion began [20]. Additionally, the system was robust and sensitive to different motion speeds and different object locations, since the surface EMG signals could differentiate the different activations of the muscles [20].

Wearable technology devices and systems often pose challenges such as the availability of constrained energy sources, the restrictions in size, as well as limitations in the computational resources [19]. Two studies focused on optimizing the transmission [23] and the design choices [19] for the control systems of prosthetic hands. For instance, Wang and colleagues developed a wearable functional electrical stimulation system for the real—time control of intentional hand motor function [23]. This study optimized the surface EMG thresholds and parameters for effective transmission of information between healthy and paralyzed limbs to improve the voluntary participation of hemiplegic patients during their rehabilitation training [23]. Choosing the optimal sEMG thresholds is particularly important, as these thresholds are used to classify motion and regulate the electrical stimulation frequency during therapy [23]. The prototype was developed to ensure a reduction in cost, power, and size for suitability of rehabilitation purposes at home [23]. In another study, Brunelli and colleagues optimized the design considerations to develop a wearable system for prosthetic hand control based on sEMG signals [19]. Their system included real-time data acquisition from 32 sEMG channels to ensure the wireless streaming was reliable [19].

However, Tavakoli and colleagues report that advances in prosthetic terminals require many control inputs to control the system, and using multiple sEMG channels raise the cost and complexity of the system [24]. Many amputees prefer to use a light weight and simple prosthetic device, instead [24]. One study developed a fast, simple, and low cost prosthetic device which can recognize up to four gestures, including single/double wrist flexion and hand opening/closing, using a single sEMG channel [24]. A problem that is often prevalent in EMG-based control of prosthetic devices is the misinterpretation of background noises or the misclassification of other hand movements as a gesture [24]. Hence, another novelty and innovative aspect of this device which utilizes only a single sEMG channel is that a lock gesture was also added to better control the prosthetic, which would ensure that while the system is locked, no other gestures are classified [24]. The results from the development of this single channel sEMG based prosthetic indicated that 90% accuracy can be achieved, and compared to multi-channel systems, it is less costly, less bulky, consumes less energy, and can potentially be easier to use [24].

While these four studies focused on developing wearable robotic devices for rehabilitation or substitution of limbs, one study developed a novel EMG control interface to control the motion and joints compliance of an extra, supernumerary robotic limb [25]. The design of this prosthetic system enables the user to directly control the stiffness of the robotic finger with a single surface EMG channel [25]. Furthermore, the integration of two EMG control interfaces in their system allow the continuous recording of EMG variation in the biceps, and its amplitude is used to regulate the tightness of the grasp, while simultaneously a second EMG interface is used to differentiate hand gestures related to motions of the robotic finger [25]. Another innovative aspect of this device is that it can be used both by chronic stroke patients to compensate for their missing grasp abilities and also by healthy human individuals in order to use the robotic finger as an extra thumb to increase their hand dexterity [25].

C. Electromyography signals as a medical tool

The remaining five of the selected studies focused on developing methods in which EMG signals can be used as a medical tool. For example, one study developed a method using EMG signals to select the appropriate positions for inserting stimulating electrodes into patients with paralyzed muscles who need transcutaneous activation of the muscles with electrical stimulation [26]. It is often a challenge in this procedure to swiftly and easily determine the number of electrodes which are needed and identify their relative positions to the excitable tissue [26]. Hence, Maneski and colleagues developed this method where EMG activity maps estimated from signals recorded from paretic and non-paretic forearms can be used to predict the proper electrode positions [26]. Their results revealed that the areas with significant differences in the EMG signals between the paretic and nonparetic arms were the stimulation sites and zones unique to each individual [26]. Furthermore, this method for identifying the stimulation sites is advantageous, as it does not require dynamometers in clinical applications or kinematic sensors, the stimulation sites can be observed visually, and the method is robust enough to enable any EMG recording system with a mapping software to be used [26].

Two studies focused on the relationship between lip movements and surface electromyography. For instance, one study developed a patient specific three dimensional lip model by using facial surface electromyography signals to accurately predict the consequences of oral cancer surgery [27]. Although surgery is the typical route for treatment of oral cancer [28], the procedure can lead to the loss of functions such as swallowing, mastication, and speech [29]. Under these circumstances, the tumor is deemed inoperable and alternate treatments, such as chemoradiotherapy, would need to be considered [30]. As such, it is crucial to be able to accurately predict the consequences of oral cancer surgery to be able to determine the right treatment for a patient [31]. Since predicting the consequences of the surgery is not reliable and often subjective, Eskes and colleagues designed this 3D lip movement model based on sEMG signals. The facial surface EMG signals provided information for patient-specific activation patterns, which in turn were used to derive an empirical model to control the dynamic lip movements in the 3D model [27]. The information developed from their model can then be incorporated into a biomechanical model to perform virtual surgery and determine the functional outcomes after the procedure [27].

While the study focused on developing the lip model was intended to prevent masticatory degeneration, another study developed a real-time, sEMG signal based trajectory for a masticatory rehabilitation robot [32]. This study marked the first time that a continuous masticatory motion profile had been reproduced by a robot [32]. Mastication is a complicated process involving grinding and clenching, and disorders which are associated with mastication can reduce a person's ability to open and close their mouth, thereby decreasing his or her quality of life [32]. Thus, a robot's ability to program rehabilitation sessions with different intensities and its ability to reproduce movements make it an ideal candidate for implementing rehabilitation strategies [33]. Since sEMG signals can be used to identify differences in chewing patterns among individuals, Kalani and colleagues developed a robot which is controlled by these signals to reproduce the masticatory process in a human jaw [32]. Hence, this robot can help in rehabilitation by reproducing the extent to which a mouth should be opened and closed for the required masticatory motion in a patient's jaw [32].

Two studies were able to show that EMG signals can be used to diagnose particular diseases and disorders in patients. For example, one study determined that median frequency values of surface EMG signals in patients with temporomandibular disorders (TMD) were significantly higher than healthy individuals [34]. TMD is a disorder which leads to degeneration in mastication and jaw movements [34] and many individuals with this disorder also suffer from a myriad of psychological health issues, such as depression, stress, and anxiety [35]. Although the presence or absence of TMD is currently identified by clinical examination [36], there exists a need to improve and develop better diagnostic methods. Hence, this study conducted by Politti and colleagues contributed to this field, as their results indicated that a range of frequency bands between 20 and 100 Hz gave rise to significant differences between healthy and TMD subjects [34]. This study contributed to the field by showing that a non-invasive technique using sEMG signals can be used to quantitatively identify TMD dysfunctions [34]. In a separate study, researchers discovered alterations in EMG patterns in diabetic subjects with diabetic peripheral neuropathy (DPN) and without DPN during stair ascending and descending [37]. DPN is a typical chronic complication of diabetes mellitus causing motor control alterations that affect the foot [37]. The study also determined that early lower limb surface EMG activity occurred in subjects who were able to perform tasks such as stair ascending, stair descending, and level walking faster [37]. These results suggested that patients with DPN were unable to control their weight bearing efficiently while climbing or descending stairs [37], and thus the results can be used to develop training interventions to improve muscle activation in neuropathic patients [38].

IV. DISCUSSION

The purpose of this study was to conduct a systematic literature review and synthesize the most recent advances in the field of electromyography for innovative biomedical applications. A total of thirteen studies published between 2016 and May of 2017 were identified which focused on three key areas: electromyography based wearables to address a solution to a problem, electromyography based wearables for prosthetics, and electromyography signals as a medical tool.

Although research on this topic has been an ongoing investigation spanning four continents, it is noteworthy that only one study, from the United States, has been conducted in North America. As indicated by the results from this systematic literature review, there exists a wide range of innovative biomedical applications for electromyography, from its applications in medicine and surgical procedures to prosthetic technology and even in devices which are used daily by people. The results from the review seemed to indicate that Europe, and in particular Italy, is paving the way for innovation in electromyography. In fact, Italy is the only country to have published studies on this research topic in all three areas of biomedical innovations. Thus, there is a need for studies to focus on North America as a context to investigate this area, especially considering that eight of these thirteen selected studies have developed wearable technology. Nasir and Yurder report that growth in the global wearable devices market is steadily growing and is expected to garner great business potential as consumers' interest and awareness in wearable technologies also grow [9]. Although back in 2014, Myers and colleagues developed novel wearable EMG sensors based on nanowire technology [39], no other notable wearable devices based on biomedical applications of EMG have been developed in the last one year, except for the American Sign Language recognition system designed by Wu and colleagues. It is also important to note that no studies have focused on Canada as a context. Thus, there is a need for more North American based research and investment in this field in order to remain competitive in the wearable technologies and devices market.

In all five studies which developed surface electromyography based control of prosthetics, the prosthetic devices were all intended for upper limbs such as the hands and arms. There appears to be a lack of studies which utilize sEMG technologies for controlling prosthetics associated with other parts of the body, such as the legs or feet in the lower limbs. Thus, the development of EMG based prosthetics of lower limbs ought to be examined for future research in order to potentially help lower limb amputees and those who need rehabilitation due to a degeneration in their gait. The results from the systematic literature review also revealed the need for a compromise between the number of gestures a prosthetic device can recognize and its number of surface EMG channels. The studies indicated that accurate recognition of the hand and arm gestures by the sEMG technology is important to ensure the comfort and usability of the prosthetics. However, increasing the number of gestures required an increase in the number of sEMG channels which had to be used to control the system. When the number of sEMG channels increased, it led to an immediate increase in the complexity, cost, and weight of the entire prosthetic device. For example, the prosthetic hand device developed by Brunelli and colleagues utilized 32 sEMG channels to ensure wireless streaming was reliable for efficient signal acquisition and processing. In order to minimize the number of channels, Tavakoli and colleagues attempted to design a prosthetic hand control system utilizing only a single sEMG channel, which restricted the number of recognizable gestures to four. Thus, future research needs to investigate a compromise between the number of sEMG channels and recognizable gestures in order to optimize prosthetic hand control and its efficacy.

This systematic literature review was limited to articles published in English. Hence, any relevant research conducted and published in a language other than English may have been missed. The review was also limited to articles published from January 2016 to May 2017, and therefore any relevant articles which were recent but not published within this specific time frame may have been omitted. Furthermore, this study was conducted using four databases and only published papers were included. As such, it is possible that any relevant research currently under review for publication may have been missed. The heterogeneity in the studies and the fact that each study investigated a different aspect of a potential innovative biomedical application of electromyography did not make it possible to compare the studies and perform a meta-analysis. Thus, perhaps future systematic literature reviews on this topic can focus on only one of the three key areas of innovative biomedical applications identified in this paper. Widening the time frame and focusing on only one aspect may enable an in-depth investigation into this research topic.

REFERENCES

[1] E. Criswell, *Cram's Introduction to Surface Electromyography*, 2nd ed. Sudbury, MA: Jones and Bartlett Publishers, 2010, pp. xv – 5.

[2] G. Kamen and D.A. Gabriel, *Essentials of Electromyography*. Champaign, IL: Human Kinetics, 2010, pp. 2

[3] R. Merletti and P.A. Parker, *Electromyography: Physiology, Engineering, and Non-invasive Applications*, vol. 11. Hoboken, NJ: John Wiley and Sons Inc. Publications, 2004, pp. xv.

[4] D. Farina, R. Merletti, and D.F. Stegemen, "Biophysics of the generation of EMG signals," in *Electromyography: Physiology, Engineering, and Non-invasive Applications*, vol. 11, R. Merletti and P.A. Parker, Ed.. Hoboken, NJ: John Wiley and Sons Inc. Publications, 2004, pp. 81 – 102.

[5] L. Bareket *et al.*, "Temporary-tattoo for long-term high fidelity biopotential recordings," *Nature Scientific Reports*, vol. 6, May 2016.

[6] P. Frankelius, "Questioning two myths in innovation literature," *Journal of High Technology Management Research*, vol. 20, pp. 40 – 51, 2009.

[7] Z. Khan, "All tatted up", *The Iron Otis*, pp. 1, Sept. 2016.

[8] P. Jacso, "The impact of Eugene Garfield through the prism of Web of Science," *Annals of library and Information Studies*, vol. 57, pp.222 – 247, Sept. 2010.

[9] S. Nasir and Y. Yurder, "Consumers' and physicians' perceptions about high tech wearable health products," Procedia – Social and Behavioral Sciences, vol. 195, pp. 1261 – 1267, July 2015.

[10] S.C. Jeong *et al.*, "Domain-specific innovativeness and new product adoption: A case of wearable devices," *Telematics and Informatics*, vol. 34, no. 5, pp. 399 – 412, Aug. 2017.

[11] M. R. Golab, P. J. Breedon, and M. Vloeberghs, "A wearable headset for monitoring electromyography responses within spinal surgery," *Eur. Spine J.*, vol. 25, no. 10, pp. 3214–3219, Oct. 2016.

[12] J. Wu, L. Sun, and R. Jafari, "A Wearable System for Recognizing American Sign Language in Real-Time Using IMU and Surface EMG Sensors," *IEEE J. Biomed. Health Inform.*, vol. 20, no. 5, pp. 1281–1290, Sep. 2016

[13] D. Barberis *et al.*, "Language resources for computer assisted translation from italian to italian sign language of deaf people," presented at the Accessibility Reaching Everywhere AEGIS Workshop Int. Conf., Brussels, Belgium, Nov. 2011.

[14] A. B. Grieve-Smith, "SignSynth: A sign language synthesis application usingweb3d and perl," in *Gesture and Sign Language in Human-Computer Interaction*. New York, NY, USA: Springer, 2002, pp. 134–145.

[15] Y. Li *et al.*, "A sign-componentbased framework for chinese sign language recognition using accelerometer rand sEMG data," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 10, pp. 2695–2704, Oct. 2012.

[16] G. Biagetti *et al.*, "Wireless Surface Electromyograph and Electrocardiograph System on 802.15.4," *Ieee Trans. Consum. Electron.*, vol. 62, no. 3, pp. 258–266, Aug. 2016.

[17] J. S. Karlsson *et al.*, "Wireless monitoring of heart rate and electromyographic signals using a smart T-shirt," *in Proc. International Workshop on Wearable Micro and Nanosystems for Personalised Health*. Valencia, Spain, May 2008.

[18] A. Burns *et al.*, "SHIMMER: An extensible platform for physiological signal capture," *in Proc. Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Buenos Aires, Argentina, pp. 3759-3762, Aug. 2010.

[19] D. Brunelli *et al.*, "Design Considerations for Wireless Acquisition of Multichannel sEMG Signals in Prosthetic Hand Control," *Ieee Sens. J.*, vol. 16, no. 23, pp. 8338–8347, Dec. 2016.

[20] I. Batzianoulis *et al.*, "EMG-based decoding of grasp gestures in reaching-to-grasping motions," *Robot. Auton. Syst.*, vol. 91, pp. 59–70, May 2017.

[21] E. Biddiss, "Need-directed design of prostheses and enabling resource," in *Amputation, Prosthesis Use, and Phantom Limb Pain: An Interdisciplinary Perspective*, vol. 12, Craig Murray, Ed., New York, NY: Springer Science and Business Media, 2010, pp. 7 – 22.

[22] P. Maciejasz *et al.*, "A survey on robotic devices for upper limb rehabilitation," *J. Neuroeng. Rehabil*, vol.11, no. 3, Jan. 2014.

[23] H.P. Wang *et al.*, "Real-time and wearable functional electrical stimulation system for volitional hand motor function control using the electromyography bridge method," *Neural Regen. Res.*, vol. 12, no. 1, pp. 133–142, Jan. 2017.

[24] M. Tavakoli, C. Benussi, and J. L. Lourenco, “Single channel surface EMG control of advanced prosthetic hands: A simple, low cost and efficient approach,” *Expert Syst. Appl.*, vol. 79, pp. 322–332, Aug. 2017.

[25] I. Hussain *et al*., “An EMG Interface for the Control of Motion and Compliance of a Supernumerary Robotic Finger,” *Front. Neurorobotics*, vol. 10, p. 18, Nov. 2016.

[26] L. P. Maneski *et al*., “Stimulation map for control of functional grasp based on multi-channel EMG recordings,” *Med. Eng. Phys.*, vol. 38, no. 11, pp. 1251–1259, Nov. 2016.

[27] M. Eskes *et al.*, “Predicting 3D lip movement using facial sEMG: a first step towards estimating functional and aesthetic outcome of oral cancer surgery,” *Med. Biol. Eng. Comput. Heidelb.*, vol. 55, no. 4, pp. 573–583, Apr. 2017.

[28] J.P. Shah and Z. Gil, “Current concepts in management of oral cancer-surgery,” *Oral Oncol.* vol.45, no. 4-5, pp. 394–401, April 2009.

[29] A.M. Kreeft *et al*., “The surgical dilemma of “functional inoperability” in oral and oropharyngeal cancer: current consensus on operability with regard to functional results,” *Clin. Otolaryngol,* vol. 34, no. 2, pp. 140–146, April 2009.

[30] A.M. Kreeft *et al*., “The surgical dilemma in advanced oral and oropharyngeal cancer: how we do it,” *Clin Otolaryngol,* vol. 36, no. 3, pp.260–266, June 2011.

[31] M. J. A. van Alphen *et al*., “Towards virtual surgery in oral cancer to predict postoperative oral functions preoperatively,” *Br J Oral Maxillofac Surg,* vol. 51, no. 8, pp.747–751, Dec. 2013.

[32] H. Kalani, S. Moghimi, and A. Akbarzadeh, “Towards an SEMG-based tele-operated robot for masticatory rehabilitation,” *Comput. Biol. Med. Oxf.*, vol. 75, pp. 243–256, Aug. 2016.

[33] V. Huang and J. Krakauer, “Robotic neurorehabilitation: a computational motor learning perspective,” *J. NeuroEng. Rehabil*., vol. 6, no. 6, pp. 1 – 13, Jan. 2009.

[34] F. Politti *et al.*, “Characteristics of EMG frequency bands in temporomandibullar disorders patients,” *J. Electromyogr. Kinesiol.*, vol. 31, pp. 119–125, Dec. 2016.

[35] S. Kindler *et al*., “Depressive and anxiety symptoms as risk factors for temporomandibular joint pain: a prospective cohort study in the general population,” *J. Pain Off. J. Am. Pain Soc*. vol. 13, no. 12, pp. 1188–1197, Dec. 2012.

[36] D. Manfredini *et al*., “Temporomandibular disorders assessment: medicolegal considerations in the evidence-based era,” *J. Oral Rehabil*. vol. 38, no. 2, pp. 101–119, Feb. 2011.

[37] F. Spolaor *et al*., “Altered EMG patterns in diabetic neuropathic and not neuropathic patients during step ascending and descending,” *J. Electromyogr. Kinesiol.*, vol. 31, pp. 32–39, Dec. 2016.

[38] M. G. Benedetti *et al*., “Muscle activation patterns during level walking and stair ambulation,” in *Applications of EMG in Clinical and Sports Medicine*, C. Steele, Ed., InTech, 2012.

[39] A. Myers *et al*., “Novel wearable EMG sensors based on nanowire technology,” *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, pp. 1674 – 1677. 2014.