A Wearable Sit-to-Stand Detection System Based on Angle Tracking and Lower Limb EMG

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***Abstract*—Sit-to-stand (STS) failures represent one type of fall accidents caused by loss of balance on senior citizens when they are trying to make body movement from sitting to standing. For effective detection of STS failures, a wearable STS detection system was proposed and developed in this study, based on the combination of the angle change data collected from people's upper trunk and the electromyography (EMG) data acquired from quadriceps. The developed STS detection system will raise an alarm when the user (such as elderly people or people with disabilities) tries to stand up or at least intend to stand up without proper care or necessary assistance. In such a case, the caregiver will be promptly notified and can come to provide necessary assistance to the user before STS failure happens. Experimental results showed that the developed system can work successfully on different human subjects with the FAR (false accept rate) and FRR (false reject rate) below 5%. It has been demonstrated that the proposed approach holds the advantages in terms of early alarms (i.e., reported at early stage of STS procedure), accurate detection, low false alarm rate, low cost, as well as ease-of-use, all of which have made the proposed system suitable for being adopted and integrated in other pervasive healthcare applications.**

I. Introduction

Hundreds of thousands of stroke patients who lose standing ability fall every year, when they try to get off from the seat. Severe injuries to people are often reported as a result of sit-to-stand fall accidents, such as hip fractures and head traumas, and can potentially increase the risk of early death. Every year approximately one-third of the community-dwelling population aged 65 years and older experiences a fall at least once, and by the age of 80 this proportion increases to 50% [1].

Fortunately, thanks to the advances and rapid development of wearable body sensors and mobile health ("mHealth") technology, accurate and timely detection of sit-to-stand activities becomes possible and feasible nowadays. In this study, through measuring relevant physiological and behavioral characteristics involved in the STS procedure, an early alerting system for STS detection was proposed and developed. The details of the proposed approach is introduced in Section III.

A. Sit-to-Stand (STS) Procedure

STS represents the rising movement from a chair or other seats, which is based on a series of physical actions, including the support transfer from seat to feet, the forward and upward movements of the gravity center, and the knee extension. Many parameters will be changed in a simple STS procedure. Support transfer from seat to feet will result in increased muscle activities on thigh, shank and even waist. Forward movement of the gravity center is resulted from the motion of leaning forward of the upper trunk. Knee extension will lead to an increase of the distance between the centers of the thigh and the shank. Fig. 1 illustrates the change of the upper trunk angle during a typical STS procedure [2]. The angle θ between the vertical and the upper trunk will increase until it reaches a maximum value and then decrease to zero, within one STS cycle. A prior study [3] showed that the Quadriceps and Tibialis anterior contributed most in a STS procedure and the height of the seat did not remarkably affect the distribution of muscle activation. In this study, we verified and proved the correctness of such observations in our experiments.

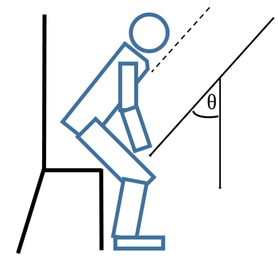

Fig. 1. Change of the upper trunk angle during the STS procedure

B. Diverse STS Procedures among Different Age Groups

STS procedures vary among people of different age groups. And even for the same age group, people may still show some sort of variations in the STS procedure. Therefore, to accurately detect the STS, it is imperative to capture the diversity among people of different age groups and eliminate the deviation among people of the same age. STS procedure can be roughly divided into three phases for the convenience of analysis. As shown in Fig. 2 [4], for young adults, a full STS procedure only takes 1-1.5 seconds; while for elder people, a much longer STS procedure is demanded. Taking the rising phase of elder people as an example, the first stage of STS can be defined as from 0 to 1.5 seconds, representing the motion of

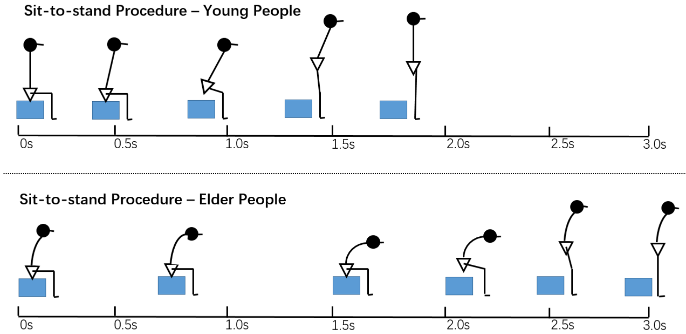

Fig. 2. Stages of STS procedure [4]

leaning in which people are leaning their upper trunk forward and contracting the muscles on their legs, but their hips are still staying on and adhering to the seat. The second stage is from 1.5 seconds to 2.0 seconds, during which people's hip gets off from the seat and the angle of the upper body θ reaches its maximum level. The third stage is from 2.0 seconds to 2.5 seconds which has seen a significant upward movement for the standing people and θ begins to decrease until it reaches 0 (i.e., aligned with the vertical axis). At the same time, knees have an extension and keep straight at the last moment of the STS procedure. According to the three STS stages defined above, it is clear that an effective STS detection system has to be able to raise an alarm during the first two stages. Because the third stage of STS procedure will be very dangerous for the stroke or elder people who have lost their abilities to stand firmly. Actually, most of STS failures occur during the third stages, and those failures may result in body injuries or even more severe consequences. In the third stage, body gravity center has already been raised, which means the force will be very large when people's body hits the ground.

Furthermore, it has been reported that [5], for people who have difficulties to stand up, such as the elderly and stroke or Parkinson patients, the duration of their STS procedures could be much longer than 2.5 seconds. Table I [5] shows the means and standard deviations of the STS time for the people older than 75 (based on five-times STS tests). Those elderly people who have stroke or Parkinson usually demand over 10 seconds for the STS procedure, far more than the 2.5 seconds average STS time for general population. This finding indicates that the elderly population may need 12 seconds or even more time to get into the third stage of STS, and thus potentially allows us to detect the STS activities in a timely manner and raise the alarm in the earlier stages of STS (e.g., at the very beginning of the second stage) to notify caregivers before a STS failure happens. Furthermore, those stroke or Parkinson people often need several back-and-forth rounds between the stage 1 and the stage 2, before eventually entering the stage 3 of STS procedure. In this case, our STS detection system can properly detect the STS activities and raise the alarm when people are entering the stage 2 of STS for the first time. An even more ample response time can be provided by our developed system to the caregivers of nursing homes or other long-term care facilities for proper preventive actions.

TABLE I
STS TIME (IN SECOND) BY AGE AND GENDER [5]

Age Group	Men Mean (SD)	Women Mean (SD)
75-79	12.1 (5.4)	12.2 (4.1)
80-84	12.9 (5.5)	13.4 (5.6)
85-89	13.7 (7.2)	14.1 (6.5)
90+	17.2 (9.0)	15.1 (6.5)
Total	12.8 (5.9)	12.9 (5.1)

II. Related Work

Extensive research has been presented in literature for sit-to-stand detection, which can be classified into three categories: motion sensor based approaches, video detection based approaches, and pressure/contact sensor based approaches.

A popular approach for STS detection is to utilize motion sensors to analyze the sit-to-stand procedures [5]–[8]. Lord *et al.* [5] used gyroscope attached to the subject's chest to analyze the sit-to-stand transition and duration time for elder people. Doheny *et al.* [6] deployed several accelerometers on the subject's chest and thighs. According the data from accelerometers during 4 FTSS (Five Times Sit-to-stand) sessions on each subject, fall prediction and classification were implemented. Fuschillo *et al.* [7] presented an accelerometer-based method to predict the center of pressure and center of mass during sit-to-stand movement. And Janssen *et al.* [8] used accelerometric balance parameters to evaluate a STS procedure. The motion sensor based methods have been proven to be very effective for analyzing the STS procedure and they can also provide some clues for physicians to conclude a decision about whether a STS failure will likely happen to the individual. However, this approach is not suitable for instantaneous STS detection, because lower limb motions will not be involved until the later stage of a STS procedure, and a detection mechanism purely relying on upper body motions will produce too many false alarms. Moreover, the motion sensor based STS detection system is not suitable for being used on a moving wheelchair, since the wheelchair movement will produce a lot of false alarms.

The video based STS detection system seeks to detect the sit-to-stand movement based on the video data from one or several real-time surveillance cameras. For example, Banerjee *et al.* [9] developed a detection system to evaluate the fall risk of STS procedures based on the fuzzy clustering techniques. Ke *et al.* [10] introduced an algorithm which can detect the movements according volumetric features of human body under cameras. This technique can also be used to detect a sit-to-stand movement. There are many advantages for video based STS detection system, since no extra device or accessory is attached on human body and multiple targets detection can be achieved using one system. However, the major concern about invasion of privacy under cameras prevents the adoption of such approach in private environments, such as bedrooms or restrooms, where STS failures happen most frequently.

Pressure/contact sensor based approach has gained increasing attention and becomes a more compelling method for STS detection [11], [12], which has also been available in some commercial products on the market, such as the force/contact detection pad used on the chair. However, those chair pads suffer from the key limitations, in terms of late detection or massive false alarms. To this end, in the study we aim to propose a new STS detection approach that can overcome those limitations and achieve early, accurate STS detection, by leveraging recent mobile and wearable sensor technologies.

III. Approach

In this section, we introduce the rationale of our STS detection system and how it can work well for stroke or Parkinson elder people. Our STS detection system is based on two types of sensory data being collected. The first type of data is the angle θ between the upper trunk and the vertical axis (as shown in Fig. 1). The second one is the electromyography (EMG) signals from the quadriceps. When both the EMG signals and the angle θ are out of the range of the preset thresholds, the system will raise an alarm. We introduce how to acquire these two signals and how these two signals will be used in the STS detection in the following sections.

A. Acquisition of Upper Trunk Angle θ

A Moto G smartphone (Android 5.0.1 system, 1GB RAM, Qualcomm Snapdragon 400 1.20 GHz processor) was used to capture the angle of upper trunk θ. The orientation sensor inside the smartphone can directly get the tile forward angle of the upper trunk. When the human subject leans his/her upper trunk forward by a large extent, one of the pre-conditions of alerting (angle θ) will be fulfilled.

If the smartphone was placed on the chest of subjects, it would be more intrusive and inconvenient to the subjects, as well as more vulnerable to the varying posture of upper body. That is, a rather high position on the upper trunk for smartphone placement can lead to the inaccuracy caused by different postures (e.g., hunchback or not). In contrast, a lower position will always make our system less sensitive to the angle change. With the goal of achieving a balance between accuracy and sensitivity, the smartphone was placed straight up and facing forward on the central back of subjects. The placement was also required to be fixed and fastened tightly to prevent subjects from moving the smartphone intentionally.

B. Acquisition of Lower Limb EMG

EMG is an electrodiagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles [13]. Muscle cell activities can produce electric current and cause potential differences on people' skin surface, which can be received and recorded by instrument.

The device we used to collect EMG signals in the proposed STS detection system is the Shimmer 3 EMG Development Kit from the Shimmer Sensing (Boston, MA), which provides a configurable digital front-end, optimized for the measurement of physiological signals. The surface electrodes in the Shimmer kit can significantly reduce potential hazards to the wearer's skin and the chance of infection will be reduced to near none. The Moto G smartphone was paired with the Shimmer sensor through Bluetooth protocol and can continuously receive the recorded EMG signals from the sensor and write into a plaintext file with time stamps.

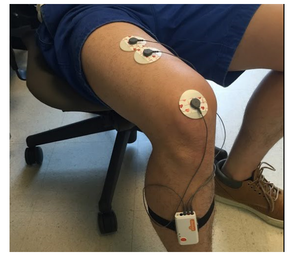

Fig. 3. Placement of EMG Sensor Electrodes

According to the distribution of muscle activities involved in a standard STS procedure discussed in prior sections, it is acknowledged that Quadriceps and Tibialis Anterior contribute most in STS. To reduce false alarms, Tibialis Anterior (TA) is excluded from our consideration, because it is relatively easy to trigger the TA activities and thus produce a large EMG potential difference. For example, some people have the habit to keep shaking their legs, when they are sitting on the seats. For the activity of "shaking one's leg," a large EMG potential deference will be produced by TA, but not by Quadriceps. If we use TA as the muscle from where we acquire the EMG signal, a false alarm will be raised if the individual happens to lean forward his/her upper trunk while he/she is shaking his/her leg on the seat. In contrast, Quadricep is a perfect muscle offering the desired EMG signals for the STS detection. Because, based on hundreds of tests, Quadriceps produce a large potential difference only in the condition of STS (in the beginning of STS Stage 2, Quadriceps will produce a significant large EMG signal).

1) Interferences Removal for EMG Acquisition: Fig. 3 illustrates the placement of three EMG sensor electrodes. The electrode placed on the knee is used as the reference point, because there is nearly no muscle activity around that region, and the other two electrodes placed on the thigh represent the positive and negative input channels of the EMG signal. Through this configuration, common-mode noises or interferences introduced during EMG measurement can be mitigated by subtracting the two samples from those two electrodes respectively. Furthermore, the placement of the central signal aggregation and wireless communication module on the shank can help improve stability of wire and sensor placements.

To eliminate the variations caused by different subjects, a normalized difference value which is dynamically updated between EMGs during rest and STS is used to measure the EMG change on quadriceps. The algorithm calculates the first average EMG value in 2 sec and updates this value every 0.02 sec (the EMG sample rate is 51.2 Hz for our application). When a new EMG sample is received, the application on the smartphone calculates the difference between the current average value and the new sample value. If the difference is larger than the threshold, it is asserted that the other precondition for

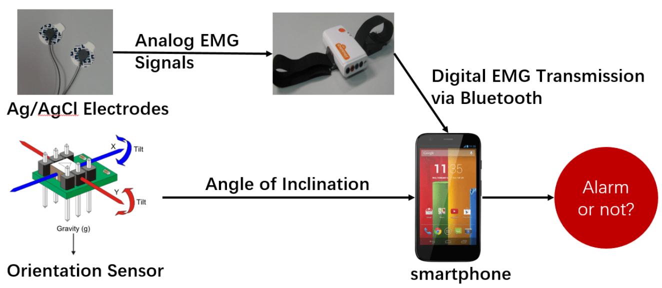

Fig. 4. Architectural Flow Diagram of STS Detection System

raising an alarm (EMG Difference) is fulfilled.

2) Signal Flow and Advantages of the STS Detection System: Fig. 4 depicts the signal flow of our proposed STS detection system. In general, electrodes attached on the leg (particularly around the area of quadriceps) collect the EMG signals and then the sensor module transmits all acquired signals to the smartphone via Bluetooth. The smartphone will aggregate the collected EMG signals and the tile forward angles of the upper trunk measured by the built-in orientation sensor, and compare against personalized thresholds to detect any potential STS activities (raising the alarm accordingly).

The synergistic combination of tilt forward angle and EMG can significantly improve the STS detection accuracy and reduce false alarms. Our proposed STS detection system carries the following advantages: fast and accurate detection of the patient's intention of getting off from the seat, which will enable prompt response of caregivers to prevent more severe injuries caused by STS failures, as well as low cost and easy to be integrated into other existing mHealth systems. It can raise an alarm immediately when the individual's hip gets off from the seat. A separation between the hip and the seat will shift the individual's body weight completely from the seat to the legs which will lead to a significant increase of muscle activities in the Quadriceps. The sample frequency of our system is around 50 Hz which means that our system can make detection decisions for every 0.02 seconds. The system can promptly capture the moment at the beginning of stage 2 of STS procedure which can be considered as an intention to get off from the seat.

IV. Experiment

A. Experimental Setting

Three subjects of age 24 to 26 and three subjects of age 67 to 73 participated in our STS detection experiments. This study was reviewed and approved by the Binghamton University Institutional Review Board (IRB). Each subject was required to do sit-to-stand and stand-to-sit actions three times separately from the chair that had been adjusted to three different height settings (high, medium, low). Same STS actions were also repeated by each subject on a wheelchair with a medium height setting. Fetching a pen on the table in front of the subject without leaving from the seat was executed by every subject in order to evaluate the system's FAR (an alarm should not be raised, but actually it is raised) in the circumstance that the subject only had an upper trunk movement but kept sitting tightly on the seat. Similar action of fetching a pen on the ground but with the hip leaving from the chair was executed to evaluate the system's FRR (an alarm should be raised, but actually it is not). The other purpose of requiring human participants to fetch a pen on the ground is to test the system's ability of detecting the subject's intention to stand up but this action fails and the subject slides down to the ground in an early stage.

In our pilot study, we sought to develop and evaluate a proof-of-concept prototype to show that the combination of upper trunk angle and Quadriceps' EMG difference can make an early detection on subjects' intention of standing up from a chair. Thus a small dataset, consisting of three young subjects and three elder subjects, was tested in our experiments. However, the experimental protocol, which required the subjects to fetch a pen on the table or on the ground with different seat heights and diverse subject groups, can provide reasonable and representative indications to show the feasibility and effectiveness of the developed system in timely detecting the intention to stand up. During the experiment, the developed application in the smartphone recorded the differences of tilt forward angles and EMG signals and then automatically wrote into a text file with timestamps 50 times in one second. Camera was used to record the whole experiment progress for every subject. According the timestamps in the video and text files, tilt forward angle and EMG data were synchronized at every moment and in different STS stages.

B. Threshold Settings

According to a prior study [14], for normal people, the upper trunk or shoulder tilt average angle is about 27.28 degree. Given the fact that our proposed system will be adopted primarily for elder people, a slightly larger threshold value should be used in our experiments. The range of angle cannot be set too large for the early detection purpose. And on the other side, a rather narrow angle range will significantly increase the false alarms. Based on our observations of the STS procedures for elder people in nursing homes, the threshold norm for upper trunk tilt is set as 30 degree.

The threshold for EMG strength was set as 16,110 (raw data, no unit) based on our extensive tests to reach a minimum equal error rate 6.266%, as show in Fig.5. The experiment was designed as follow: under the precondition that an upper trunk tilt angle threshold was set to 30 degree, for one EMG threshold value, 40 times of standing up from the seat, 30 times of fetching a pen on the table, and 30 times of fetching a pen on the ground need to be executed by another three subjects at different ages who never participated in the experiments to ensure the universality of this threshold setting and prevent over-fitting. Our system was tested for the EMG thresholds of 5,000, 7,500, 10,000, . . . , 25,000, 27,500, 30,000, respectively. According to the average FAR and FRR for each EMG threshold, as well as a 4th-level curve fitting on the average FAR and FRR respectively, an equal error rate of 6.226% was identified for the EMG threshold of 16,110.

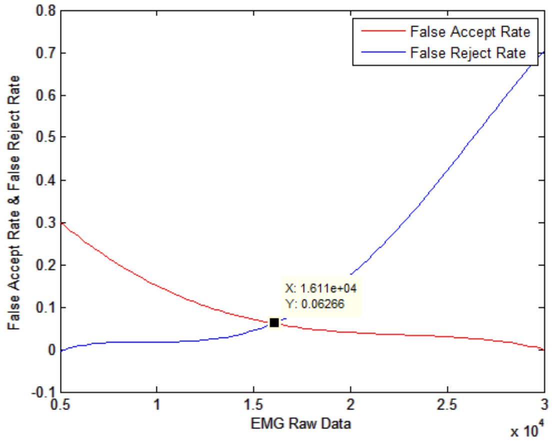

Fig. 5. EMG Threshold Settings

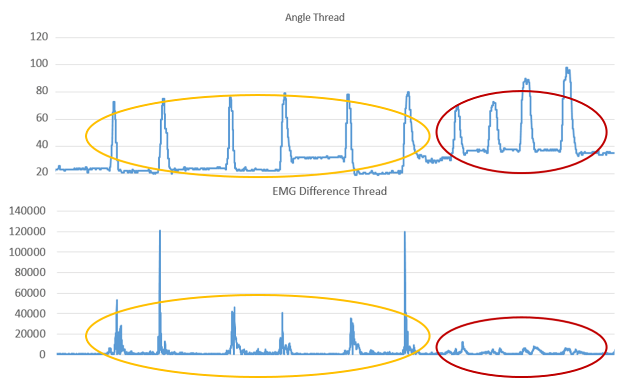

Fig. 6. Examples of Angle and EMG Data

C. Experiment Results and Analysis

1) Experiments with Young Adults: Experiments were first conducted on the 3 younger human subjects. For a total of 137 actions (most of the actions were normal standing up from the seat, one third of them were fetching a pen on the table and fetching a pen on the ground respectively), FAR was 3.2%, and FRR was only 0.8%. Table 2 shows the result details for each subject. In total 137 activities (both sanding up and sitting down are counted as one activity), only 4 false acceptances and 1 false rejects were observed. All the 4 false acceptances occurred when the subjects were fetching the pen on table. From careful observation on videos, during all these 4 false acceptances, the subjects were moving their body gravity centers forward a lot to try to fetch the pen on the table. And during the other 49 fetching pen on table activities which did not produce a false alarm, the subjects were moving body gravity centers forward much less than what they did in false acceptances. The reason why situation above occurred is that a large forward movement on body gravity center will cause partial transaction of body weight support from hip to legs and trigger the quadriceps muscle to shrink. For the FRR, actually only one false reject happened when the subject 2 was sitting down. The reason for the false reject is that the siting down progress is too quick and does not give enough time for the quadriceps to fully shrink and generate a large enough EMG difference strength. For the stroke and Parkinson elder people, this false reject situation can nearly be eliminated, because either sitting down or standing up progress will have a much longer time than what young people have.

TABLE II
FAR AND FRR FOR YOUNG SUBJECTS AND ELDER SUBJECTS

	Age	Gender	FAR	FRR
Subject 1	26	Male	0%	0%
Subject 2	24	Female	4.8%	2.3%
Subject 3	25	Female	5%	0%
Average	25		3.2%	0.8%
Subject 4	69	Male	3.3%	3.3%
Subject 5	67	Male	1.4%	3.07%
Subject 6	73	Male	0%	1.37%
Average	69.67		1.17%	2.35%

According to the angle trend and EMG trend in Fig.6, EMG values and angle values fluctuate nearly at the same time during the yellow circled portions. Both angle and EMG trends have 6 fluctuations during this period of time, because the subject was instructed to stand up, keep standing and sit down for three times. Both standing up and sitting down can cause a fluctuation on the angle and EMG values. In the red circled portions, only fluctuations on the angle trend can be observed, because the subject was instructed to fetch a pen on the table while keeping sitting on and adhering to the chair. In this case, there is no body weight transfer from the hip to the legs, and also few muscle activities can be observed on quadriceps during this period of time. However, because the subject has to lean his upper trunk forward to fetch the pen, there are still fluctuations on the angle trend. The trends above can demonstrate that our developed detection system has high sensitivity for a STS and high resistance to false alarms when the subjects only have upper trunk movements but keep sitting on the seat consistently.

2) Experiments with Elderly People: To evaluate the effectiveness of the proposed approach on those population of particular interest, we further conducted experiments involving three elder participants at age 69, 67, and 73. The experimental protocols and procedures were exactly the same as the ones for the younger subjects. For a total of 170 actions (20 actions of fetching a pen on the table, 48 actions of fetching a pen on the ground, and the other 102 actions of normal standing up from the chair), only 2 false acceptances and 4 false rejections were observed. Moreover, for all normal standing up and sitting down activities, there is no false acceptance and false rejection for the 3 elder subjects. All of the 2 false acceptance happened when fetching a pen on the table, and the 4 false rejection happened when fetching a pen on the ground. A FAR of 1.17% and FFR of 2.35% have been achieved in the experiments involving the elder participants, as shown in Table III.

3) Differences between the Elderly and Young Groups: Compared with the young subject group, false accept errors and false reject errors on elder subjects are significantly less for the normal standing up activities because the elder subjects usually have a longer STS progress, which provide our system

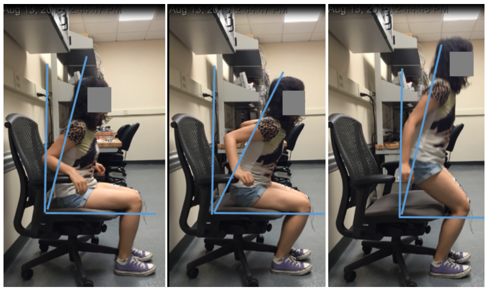

Fig. 7. Alarm trigger moment

a longer response time. Moreover, the longer the Stage 2 of a STS is, the more strength the Quadriceps need to supply. For the scenario of fetching a pen on the table, our developed system performed better on elder subjects than young subjects in terms of FAR, because young subjects tended to use their lower thunk to move the chair forward in order to fetch the pen on the table more frequently. Such a lower trunk movement when fetching a pen on the table will raise a false alarm. In the scenario of fetching a pen from the ground, young people generally performed better, because elder subjects tended to fetch the pen without a separation between the hip and the seat. In this case, our system cannot detect enough EMG strength, and the alarm will not be raised. Furthermore, according to the observations on experiment videos, fetching a pen on the ground from a higher seat will have a higher chance to raise the alarm. The reason is that the higher seat forces the subjects to use their quadriceps shrinking to control and ensure the balance of their bodies.

D. Alarm Timing

Fig. 7 presents the examples of Stage 1, 2, and 3 in a classic STS procedure. Our goal is to trigger the alarm at the beginning of Stage 2. Because for a young person, a STS process can only take 1 to 1.5 seconds. It is challenging to observe the trigger moment of our detection system. So we asked the subject to hold the body position around the Stage 2 (the middle picture in Fig. 7) and then stand up very slowly until he/she gets the Stage 3 of STS. We seek to ask young subjects to imitate an elder people's STS procedure to demonstrate that our system can meet the timing requirements of early detection. For safety concern, these experiments were not conducted on the elder subjects. But a slow playback of the recorded videos also demonstrated that our developed system can achieve early detection of STS for elder people.

V. Conclusions

In this study, a wearable STS detection system was proposed and developed, based on the changes of the upper trunk angle and the lower limb EMG strength during a sit-to-stand procedure. Our system can detect a STS intention at an earlier stage and has high resistance to false alarms (FAR is only 3.2% for young, 1.17% for elder) in the situation if people just has normal upper trunk movement but keep sitting on the chair. The low cost and high accuracy (FRR for young is only 0.8%, 2.35% for elder) make our detection system very suitable for the elder, stroke and Parkinson patients who tend to a STS failure. The integration of EMG sensors onto clothes [15], [16] could provide more flexibility, ease-of-use, and user-friendliness to our proposed approach. In the future, we can also send the alarms directly to the caregivers' smart wearable devices (e.g., smartphones or smart watches).

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