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Development of a diagnostic glove for unobtrusive measurement of chest compression force and depth during neonatal CPR

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Abstract— **Optimizing chest compression (CC) performance during neonatal cardiopulmonary resuscitation (CPR) is critical to improving survival outcomes since current clinical protocols often achieve only a fraction of the native cardiovascular perfusion. This study presents the development of a diagnostic tool to unobtrusively measure the CC depth and force during neonatal CPR using sensors mounted on a glove platform. The performance of the glove was evaluated by infant manikin tests using the two-thumb (TT) and two-finger (TF) methods of CC during simulated, unventilated neonatal CPR. The TT method yielded maximum CC depths and forces of as much as 25.7 ± 3.2 mm and 35.9 ± 2.2 N while the TF method produced CC depths and forces of as much as 21.6 ± 2.2 mm and 23.7 ± 2.9 N. These results are consistent with clinical findings which suggest that TT compression is more effective than TF compression since it produces greater CC depths and forces.**

I. INTRODUCTION

Cardiopulmonary resuscitation (CPR) in infants differs from adult CPR since cardiac arrest usually occurs as a result of a primary respiratory event [1–3]. The reported rate of survival (to hospital discharge) among infants suffering cardiac arrest ranges from 2.4% to 21% [4–6]. Among the major factors contributing to this low success rate is the poor quality (i.e., depth, duration and frequency) of chest compression (CC) during CPR [7–10]. Although chest compressions are a fairly infrequent intervention during delivery room resuscitation, occurring in 1 in 1000 term deliveries, they are, however, more common in preterm infant resuscitation (occurring in roughly 1 in 50 to 1 in 10 deliveries) [11-12]. Optimizing CC performance during neonatal resuscitation could therefore be critical to improving survival outcomes because current protocols often achieve only a fraction of the native cardiovascular perfusion even under optimal conditions [13–14]. Moreover, resuscitation of acutely ill newborns is a key competency skill of physicians and many interventions used in acute life-threatening situations are unproven and frequently unsuccessful.

The aim of this study is to present the development of a diagnostic tool which is designed to measure the CC depth and force during neonatal CPR and which allows useful insights to be obtained into CC performance during neonatal CPR.

II. METHODS

A. Diagnostic tool design and implementation

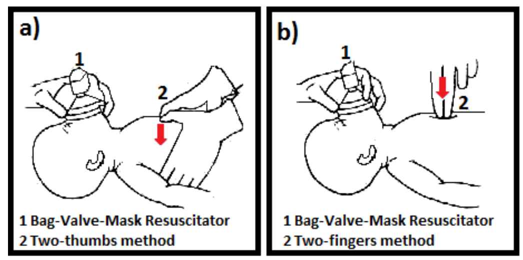

Fig.1. a) The two-thumb encircling hands CC method and b) The two-finger CC method for infant resuscitation (Adapted from [15]).

The diagnostic tool was designed to simultaneously record the CC depth and force delivered by a clinician during an entire episode of neonatal CPR, which typically lasts at least ten minutes before resuscitation efforts are discontinued [15]. Among the key design requirements for the device are that it should be: i) soft (i.e., not cause damage to the delicate skin of an infant), ii) easy to put on (i.e., not delay rapid clinical intervention), iii) reusable, and iv) capable of taking measurements when clinicians perform either the two-thumb (TT) encircling hands or two-finger (TF) CC techniques during neonatal CPR (Fig. 1).

In order to meet these design constraints a cotton, Hyflex, Ansell 11-125 glove, with rubber fingertips was selected as the diagnostic device platform because it is easy to wear and it provides a stable support for both the depth and force sensors. Since many conventional force sensors (e.g., load cells and force sensing resistors) do not provide a sufficiently soft interface they are unsuitable for the neonatal CPR application. As a result, the force sensors were fabricated from a soft, composite piezo-resistive cloth material consisting of a single layer of 1 kΩ Ex-Static® fabric sandwiched between sheets of Stretch Conductive Fabric (silver plated, 76% Nylon 24% elastic fiber), covered by layers of Neoprene®, which were glued together using Bondaweb® adhesive (Fig. 2a). The force sensors were sewn into the digits of the volar (i.e., palm) side of each glove in the distal phalanx (i.e., fingertip) position of the thumb, index and middle fingers (Fig. 2 b). A sleeve made from Neoprene® was used to electrically isolate the fingertip sensors. The CC depth was measured by 3 STMicroelectronics MEMS LIS302SG accelerometers (3-axis, ±2g analog outputs, with a sensitivity of 455mV/g) mounted on the dorsal (i.e.,

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back) side of the glove in the distal phalanx position of the thumb, index and middle fingers (Fig. 2c). Data logging was achieved with an Atmel, Atmega328p micro-controller chip and a 4GB Fujifilm, micro-SDHC card. A Turnigy Nano-tech Li-Polymer 300mAh 3.7 V battery was chosen to power the sensors, micro-controller chip and the main printed circuit board (PCB) containing an ON/OFF switch and a red indicator LED light. A Dallas Semiconductor DS3231 real time clock, powered by a Panasonic CR1220 lithium coin cell (3.3 V, 35mAh), was added to the PCB to enable synchronization of the data logging on the two gloves. The PCB (with the micro-controller chip and micro-SDHC-card) and the 3.7 V battery, were mounted on the back of the glove, above the metacarpus (i.e., intermediate part of the hand), enclosed in a Neoprene® casing attached to the glove with Velcro®.

Fig.2. a) Schematic of the composite piezo-resistive material used to fabricate the force sensor. Photographs of: b) the volar and c) dorsal sides of the diagnostic glove showing the force sensors and accelerometers.

B. Experimental Setup

The diagnostic glove's performance was evaluated by conducting unventilated, infant manikin CC tests using the setup shown in Fig. 3. The apparatus consists of an ArjoHuntleigh Contoura 300 series hospital bed, with a Pentaflex mattress. All tests were performed using a 2.3 kg Laerdal Resusci Baby™ Model 14001101 full-body, infant CPR training manikin measuring 51 cm x 15 cm x 33 cm (height x width x depth). The CC force was measured using a Tekscan 5051 Pressure Sensor pad, with 0.1N resolution, which was taped to the manikin chest and sampled data at a of 25 Hz.

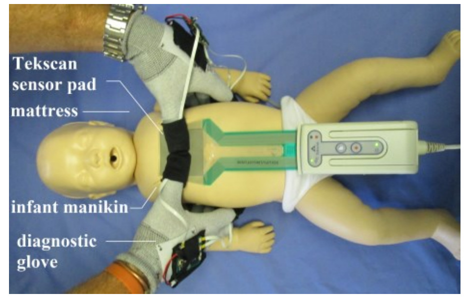

Fig.3. Photograph of the experimental setup.

C. Procedure

Prior to testing the force sensors on the fingers of the left and right gloves were calibrated, using an HBM C2 50 kg load cell over the range from 0 to 7 kg. A series of 3 tests were performed by a single, experienced clinician. In the first test CCs were performed using the TF method of CC using the left hand. While in the second and third tests the TT method and TF method using the right hand, were applied. Each test was conducted twice to ensure repeatability.

During each test the following steps were performed:

- The diagnostic gloves were put on by the clinician and the switch was turned on.
- CC was initiated by a verbal prompt.
- CC was delivered for 120 s at the American Heart Association (AHA) recommended rate of between 90 – 120 CCs p/m, with a target CC depth of 1/3rd of the anterior-posterior diameter of the infant manikin's chest (i.e., 15.0 – 25.0 mm) [15–16].
- The CC force was measured by the Tekscan pad while the acceleration and CC force were simultaneously acquired by the diagnostic gloves.

Once the tests were completed both diagnostic gloves were switched off and the micro SDHC-cards were removed.

III. Data Analysis

The data recorded by the gloves during the manikin tests were uploaded to a computer for analysis in MATLAB® (Natick, MA). The CC force was computed from the raw data based on the load cell calibration curves for each finger (Fig. 4). The CC depth, *d(t)*, was calculated by double integration of the accelerometer signals following the algorithm shown in Fig. 5, which is based on the equation:

$$\begin{aligned} d(t) &= \iint a(t).dt = \iint \left(\tilde{a}(t) + \bar{a}\right).dt = \int v(t).dt \\ &= \int \left(\tilde{v}(t) + C_v + \bar{a}.t\right).dt = \tilde{d}(t) + C_d + C_v.t + \frac{1}{2}\bar{a}.t^2 \end{aligned} \quad (1)$$

where $\bar{a}$ is the acceleration offset (i.e., the remainder after subtraction of the Earth's gravitational acceleration which arises due to imperfect calibration), C_d is the CC depth offset, C_v is the integration constant which is due to arbitrary integration starting time, $\tilde{d}(t)$ is the computed CC depth without an offset, $\tilde{v}(t)$ is the computed velocity without an offset, $v(t)$ is the velocity, $a(t)$ is the acceleration and $\tilde{a}(t)$ is the computed acceleration without an offset.

The first step in the execution of the CC depth estimation algorithm involves projecting the measured acceleration vectors onto the continuous component of the acceleration (i.e., the Earth's gravitation). The key assumption is that CC is delivered parallel to the gravitational direction. Since $\bar{a}$ and C_v both make the computed CC depth diverge with time as seen in Eq. (1) it is necessary to apply high pass filtering (HPF) to remove them, as indicated in steps 3 and 5. The cutting frequencies used were determined with respect to the AHA recommended CC rate range during neonatal CPR which corresponds to frequencies between 1.5 Hz and 2.0 Hz [15–16]. Following double integration HPF is also applied in step 7 prior to baselining, which is performed by detecting the maxima of $\tilde{d}(t)$ using double derivation and thresholding (steps 8 and 9). Once the maxima are detected they are set to zero based on an assumption of full chest decompression between compressions. The computed maximum CC depth and force data were averaged over the entire CC period and are reported as mean ± S.D in Table I.

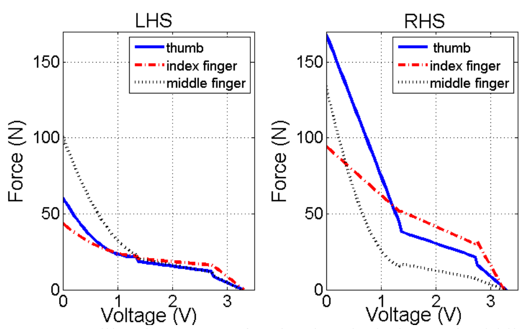

Fig.4. Force calibration curves for the thumb, index and middle finger sensors of the left and the right-hand diagnostic gloves.

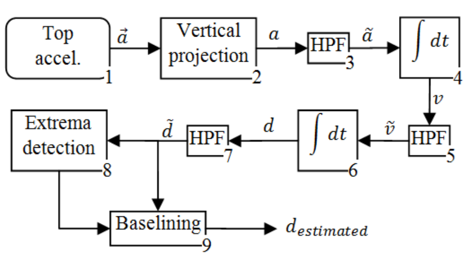

Fig.5. Algorithm for estimation of the CC depth.

TABLE I
CHEST COMPRESSION RESULTS

Test	CC method	Digit	CC depth (mm)	CC force (N) Glove	CC force (N) Tekscan
1	TF	L index finger	20.8±3.2	34.0±6.7	23.7±2.9
1	TF	L middle finger	19.3±4.7	13.5±2.2	16.5±1.9
2	TT	R thumb	25.7±3.4	52.9±0.4	32.2±3.9
2	TT	L thumb	23.9±3.4	34.0±6.0	35.9±2.2
3	TF	R index finger	21.6±2.2	26.4±1.6	22.7±2.1
3	TF	R middle finger	18.1±2.3	11.5±1.7	20.4±3.8

CC = chest compression; L = Left; R = Right; TF = two-finger CC method and TT = two-thumb CC method.

IV. RESULTS

Fig. 6 is a plot comparing the maximum CC force measured in the three test cases, for each finger using the left and right hand diagnostic glove force sensors (filled bars), as well as the Tekscan Pressure Sensor pads (unfilled bars). The figure shows that the maximum CC force measured by the gloves during the TT compression tests was 52.9 ± 0.4 N and 34.0 ± 6.0 N, for the thumbs on the left and right hand gloves, respectively. For the Tekscan pads the corresponding maximum CC force for the left and right thumbs was 35.9 ± 2.2 N and 32.2 ± 3.9 N. For the TF method of CC Fig. 6 shows that the maximum forces measured by the index and middle fingers of the left hand glove were 34.0 ± 6.7 N and 13.5 ± 2.2 N respectively, compared to 23.7 ± 2.9 N and 16.5 ± 1.9 N measured by the Tekscan pads; while the maximum forces measured by the index and middle fingers of the right hand glove were 26.4 ± 1.6 N and 11.5 ± 1.7 N respectively, compared to 22.7 ± 2.1 N and 20.4 ± 3.8 N for the Tekscan pads.

Fig. 7 is a plot comparing the maximum CC depth measured by the left and right hand diagnostic gloves during the three test cases. The figure shows that the maximum CC depth measured during the TT compression tests was 25.7 ± 3.4 mm and 23.9 ± 3.4 mm, for the left and right hand gloves, respectively. For the TF method the maximum CC depth for the left and right hands' was 20.8 ± 3.2 mm (index finger) and 21.6 ± 2.2 mm (index finger) in tests 2 and 3.

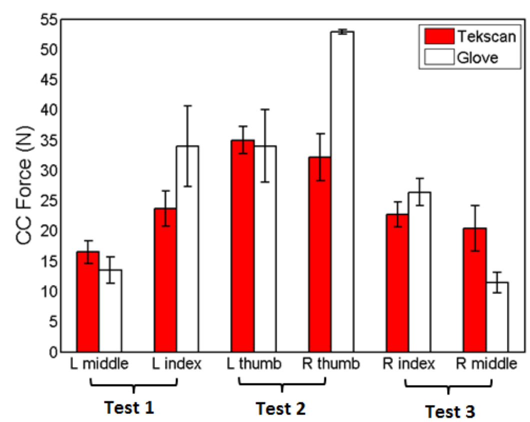

Fig. 6. CC force measured during TT and TF CPR on an infant manikin.

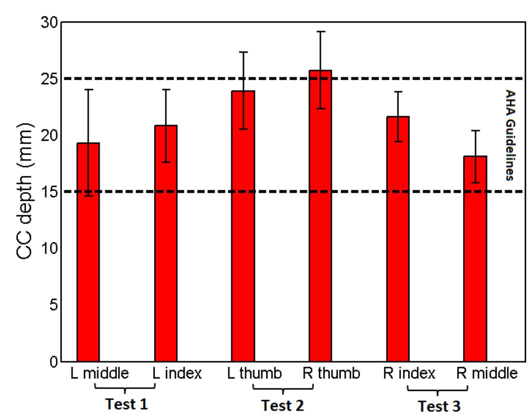

Fig. 7. CC depth measured during TT and TF CPR on an infant manikin.

V. DISCUSSION

The results shown in Fig. 6 provide several useful insights into the performance of the diagnostic gloves and into CC during neonatal CPR. Comparison of the glove data with the

Tekscan measurements reveals that some of the glove force sensors did not reliably measure the CC force. Reasonable agreement with the Tekscan measurements (within < 4 N) was achieved for the left thumb and middle finger sensors, and for the right index finger sensor. While poor agreement (within < 20 N) was achieved for the right thumb and middle finger sensors, as well as the left hand index finger sensor. This can be attributed to the fact that the force sensors are very sensitive to the contact area, which can vary due to finger curvature, glove fit and finger orientation. In spite of this deficiency, the Tekscan measurements indicate that the CC forces generated during neonatal CPR vary widely, between 16.5 N – 35.9 N, depending on the CC method used. The maximum CC force measured for the TT method was as much as 12.2 N (51.5 %) higher than maximum CC force measured for the TF method. Since sternal displacement is linearly proportional to the CC force, this suggests that the TT method should produce deeper CC depths.

Further consideration of the results presented in Figure 6 and Table I for the Tekscan measurements suggests that a higher force is always applied to one finger compared to the other. For TT compression the force produced by the left thumb was 3.7 N (11.4 %) higher than the right thumb. While for TF compression higher forces were produced by the index finger in each case, with differences of 7.2 N (43.6 %) and 2.3 N (11.3 %) respectively between the index and middle fingers of the left and right hands. These differences may be attributed in part to the fact that during the application of the appropriate neonatal CC technique, clinicians typically use one finger, to drive CC and the other for support. It is also interesting to note that the CC forces measured for the infant manikin tests (16.5 N – 35.8 N) are more than an order of magnitude smaller than the forces normally applied during manual adult CPR (300 – 500 N) [17–18].

The CC depth results presented in Fig. 7 reveal several additional insights into CC during neonatal CPR. The figure shows that the TT method of CC produces higher CC depths compared to the TF method. The difference in CC depth between the TT and TF methods varied between 2.3 mm – 7.6 mm (10.6 % – 42.0 %). This result is consistent with the force measurements shown in Fig. 6 and agrees with clinical findings reported in the literature that indicate that TT compression is more effective than the TF method [15,7]. Moreover, it is useful to note that the CC depths measured in all tests fell within the range recommended by established guidelines (15.0 – 25.0 mm) [15–16] which suggests that the glove is able to provide reasonable measurements of CC depths in the target range required for neonatal CPR.

VI. Conclusion

This study presented the development and testing of a new diagnostic tool to measure the CC depth and force during neonatal CPR using sensors mounted on a glove platform. The performance of the diagnostic gloves was evaluated by infant manikin tests using the TT and TF methods of CC. The TT method yielded mean CC depths and forces of as high as 25.7 ± 3.2 mm and 35.9 ± 2.2 N while the TF method produced index finger CC depths and forces of as much as 21.6 ± 2.2 mm and 23.7 ± 2.9 N, respectively, as well as middle finger CC depths and forces of 19.3 ± 4.7 mm and 20.4 ± 3.8 N, respectively. Taken together these results suggest that TT compression is more effective than TF compression since it produces CC depths and forces which are as much as 42.0% and 51.5% larger, respectively. Future work will focus on improving the reliability of the glove force sensors and on further manikin tests exploring the effect of ventilation on CC during neonatal CPR.

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