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A New Ecological Method for the Estimation of Nutritive Sucking Efficiency in Newborns: Measurement Principle and Experimental Assessment

Eleonora Tamilia, *Member, IEEE*, Fabrizio Taffoni, *Member, IEEE*, Emiliano Schena, *Member, IEEE,* Domenico Formica, *Member, IEEE,* Luca Ricci, *Member, IEEE*, Eugenio Guglielmelli, *Member, IEEE.*

Abstract—**The Sucking Efficiency (SEF) is one of the main parameters used to monitor and assess the sucking pattern development in infants. Since Nutritive Sucking (NS) is one of the earliest motor activity performed by infants, its objective monitoring may allow to assess neurological and motor development of newborns.**

This work proposes a new ecological and low-cost method for SEF monitoring, specifically designed for feeding bottles. The methodology, based on the measure of the hydrostatic pressure exerted by the liquid at the teat base, is presented and experimentally validated at different operative conditions.

Results show how the proposed method allows to estimate the minimum volume an infant ingests during a burst of sucks with a relative error within the range of [3-7]% depending on the inclination of the liquid reservoir.

I. Introduction

The brain development in infancy may be investigated through the assessment of early motor skills, since they can provide valuable insights into the motor control development as well as, more generally, into neural dynamics [1]. Several ecological tools, such as instrumented toys or objects [2]-[5], possibly embedding purposively developed microsensors [6], have been recently developed for investigating infants' brain development. Despite the current research on novel design methodologies for advanced wearable systems [7], such technologies result unsuitable for newborns, who show a poor motor repertoire and scarce interest in manipulating objects. On the contrary, an important motor skill that can be investigated since the first days of life is the newborns' nutritive sucking skill.

Nutritive sucks occur at about 1-Hz and are characterized by the *suction phase*, i.e., the creation of a negative intraoral pressure, and the *expression phase*, i.e., the creation of a compression pressure performed by the tongue and the palate against the nipple [7]. Series of suck cycles ending with a rest period greater than 2 s are usually referred to as *bursts* [7].

A safe and efficient nutritive sucking requires not only an efficient sucking ability, but also complex neural mechanisms [9]: previous studies report how early sucking problems may be markers of neonatal brain injury [10] and may also predict later neurodevelopmental outcomes [9][11]. In their recent review [10], Slattery *et al.* report the need for further studies on early nutritive sucking employing repeated and reliable measures. This need suggests to focus on the development of ecological tools that objectively measure sucking parameters [12]. These tools should be based on non-obtrusive technology and purposely designed to be easily used in non-structured environments also by untrained personnel: this a fundamental ecological requirement for the screening of a large number of infants also in non-clinical scenarios.

The goal of this work is to address this specific issue testing a new ecological method for the objective measurement of an important sucking parameter: the Sucking Efficiency (SEF). SEF is usually expressed as the volume of milk taken in a given interval of time divided by the number of sucks in that interval and represents one of the most important parameters for monitoring the sucking pattern developmental course [13][14].

The methods mostly used in literature for SEF estimation are not suitable for portable and low-cost devices: most of the studies estimate the milk volume intake by weighing the bottle [15] and/or by surveying the milk residual at the end [16] or during the feeding [13], implying some drawbacks related, e.g., to the measure rawness, the system non-portability [15] or the feeding interruption [13].

In order to avoid these issues, an ecological method to estimate the volume of milk intake during a burst, while meeting the requirement of portability as well, has been implemented and validated in this study.

II. Methods

A. Algorithm Definition

This study proposes a low cost method to ecologically estimate the volume of milk delivered to the newborn based on a measurement of pressure, i.e., the hydrostatic pressure of the liquid column inside the bottle at the base of the teat.

During feeding, the level of the liquid inside the bottle decreases at each suck, so at the end of each burst of sucks, when the infant ceases its sucking activity for at least 2 s, the

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Eleonora Tamilia, Fabrizio Taffoni, Domenico Formica, Luca Ricci and Eugenio Guglielmelli are with the Laboratory of Biomedical Robotics and Biomicrosystems, Università Campus Bio-Medico di Roma, Via Alvaro del Portillo, 28, 00128, Rome, Italy (e-mail: { e.tamilia; f.taffoni; d.formica; l.ricci; e.guglielmelli}@unicampus.it).

Emiliano Schena is with the Center for Integrated Research, Unit of Measurements and Biomedical Instrumentation, Università Campus Bio-Medico di Roma, Via Alvaro del Portillo, 28, 00128, Rome, Italy (e-mail: e.schena@unicampus.it).

liquid level variation may be estimated through the pressure trace offset, measured at the base of the bottle teat before and after the burst.

According to the Stevin's law, this offset is due to the height (h) of the liquid above the point where the pressure is measured. Given the density (ρ) of the liquid, this pressure may be expressed as:

$$P = h \cdot g \cdot \rho + P_t \, , \tag{1}$$

where g is the gravity acceleration and P_t is the pressure at the top of the column, which is maintained equal to the atmospheric pressure (P_{atm}) in order to eliminate the vacuum build-up within the bottle during the feeding session, as suggested by several authors [17][18].

The height of the liquid along the vertical axis depends on the bottle tilt angle (θ). So, at the beginning (t_i) of a burst, considering θ with respect to a horizontal axis (see

Fig. 1), the liquid height h is

$$h_i = l_i \cdot \sin\theta_i, \tag{2}$$

where l represents the level of liquid along the axis of the bottle, that coincides with h when the bottle is vertically tilted.

At the end of a burst, at time t_{i+1}, the liquid volume inside the reservoir is reduced by the amount corresponding to the volume taken by the infant (ΔV_{i+1}), causing a lowering of the liquid column ($h_{i+1} < h_i$) and a consequent decrease of the hydrostatic pressure

$$\Delta P_{i+1} = P_{i+1} - P_i \, . \tag{3}$$

Thus, from the previous relations, considering ρ as constant, the variation of the liquid level l, at time t_{i+1}, can be expressed as

$$\Delta l_{i+1} = \left(\frac{P_{i+1}}{\sin\theta_{i+1}} - \frac{P_i}{\sin\theta_i}\right) \cdot \frac{1}{g \cdot \rho}. \tag{4}$$

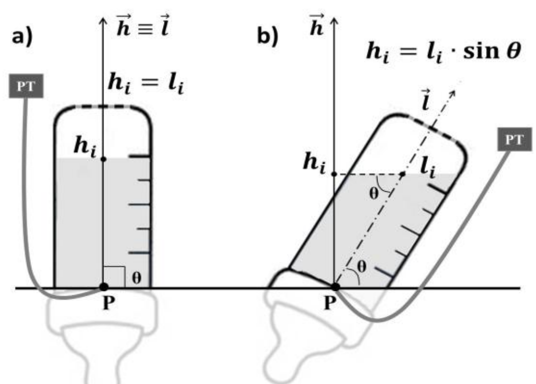

Fig. 1 Liquid column height depending on the bottle tilt angle (θ). a) at time t_i the pressure transducer (*PT*) measures the pressure exerted at the point *P* by the liquid column height h_i. b) When θ differs from 90°, the liquid column height h_i does not coincide with the liquid level l_i (taken along the bottle axis).

Since the generic variation of the volume of liquid (ΔV) inside a constant section reservoir is given by the product of the liquid level variation (Δl) and the reservoir section (S), we can obtain the following relation from (4):

$$\Delta V_{i+1} = \left(\frac{P_{i+1}}{\sin\theta_{i+1}} - \frac{P_i}{\sin\theta_i}\right) \cdot \frac{S}{g \cdot \rho}, \tag{5}$$

which enables to estimate the liquid volume variation in a burst, through the measure of the hydrostatic pressure before (t_i) and after (t_{i+1}) the burst, together with the measure of the reservoir inclination (θ_i and θ_{i+1}).

B. Experimental Setup

Experimental validation of the method for liquid volume estimation has been carried out as described below.

An open reservoir, with a constant circular section (d=27 mm, S=550 mm^2), is fastened on a vertical support allowing the orientation of the reservoir at different inclinations. The reservoir is open so that the liquid surface is always at the atmospheric pressure, as assumed in section II.A. This experimental condition can be then easily fulfilled in a real application as well, by means of a venting system that vents air at the back of the feeding bottle, maintaining the air pressure constant at 1 atm regardless of suction, as Lang *et al.* [19] report as well.

The hydrostatic pressure is measured by a low cost integrated silicon pressure sensor (MPX70002, Freescale Semiconductor: range of ±2 kPa, sensibility of 1V/kPa and accuracy of ±0.1 V). The sensor is connected to a non-compliant catheter (1.2 mm of internal diameter), inserted at the base of the reservoir, and is placed over the top of the reservoir, in order to separate the liquid media from the sensor by a column of air, that is compatible with the sensor unlike liquid media.

The inclination is estimated by a 3-axis accelerometer (ADXL330, MEMS made by Analog Devices) fixed on the reservoir, which measures acceleration with a minimum full-scale range of ±3 g and allows a static tilt estimation with a maximum error of ± 1°.

C. Measurements and Results

The performances of the proposed method have been assessed through a set of measurements of the minimum volume of interest at 3 different reservoir inclinations.

The open reservoir is filled with 50 mL of water at room temperature with a known density (ρ) equal to 1 g/cm^3. A pipette (capacity=8 mL, resolution 0.1 mL) is used to withdraw the amount of liquid corresponding to a single burst, through an electronic pipette dispenser, in order to simulate the sucking act.

The minimum volume of milk an infant ingests during a burst has been considered equal to 4 mL, according to the recent study of Taki *et al*. [20], that reports this value for newborns at 1 month of age and greater volumes at 3 and 6 months. A set of measurements are performed to verify if the proposed method enables to discriminate the minimum value of volume of interest. Hence, a volume of 4 mL of water is subtracted to the reservoir and the corresponding pressures at the beginning and at the end of the withdrawal are measured by the pressure sensor, in order to estimate the subtracted volume via the algorithm described in Section II.A. Fig. 2 shows the pressure signal during 4 consecutive trials performed with the reservoir tilted of 70°.

Such measurements are repeated at 3 different inclinations (70°, 50°, 30°) to cover the range of the possible bottle tilt angles during a feeding session. A total amount of 16 withdrawals are performed for each inclination.

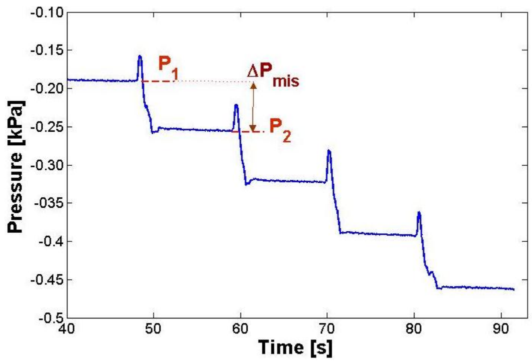

Fig. 2 Pressure signal during 4 withdrawals of 4mL of water. The reservoir tilt angle during the trials is maintained fixed at 70° and is estimated by the accelerometer output. P_1 and P_2 are the pressure values at the beginning and the end of the first withdrawal and ΔP_{mis} is the measured pressure variation. The visible peaks in the pressure trace correspond to the insertion of the pipette in the liquid.

Since the tilt angle of the reservoir is maintained constant during each liquid subtraction, the volume variation, expressed in (5), is estimated as follows

$$\Delta V = \frac{\Delta P \cdot S}{g\rho} \cdot \frac{1}{\sin\theta}. \quad (6)$$

Experimental validation is performed with water because its density is known and is lower than the milk density, whose range is [1.02-1.04] g/cm^3. Therefore, if the system results able to discriminate the ΔP generated by the subtraction of the minimum volume of water, it will be suitable also for the same application with a liquid of higher density, since the ΔP generated by the latter will be higher.

Table I reports the mean values of the measurement errors calculated as: (i) Absolute Error (AE), i.e., the absolute value of the difference between the estimated volume and the subtracted volume (4 mL); (ii) Relative Error (RE), i.e., the AE divided by the subtracted volume value. These errors are calculated for all the measurements and the RE mean values with their uncertainty (U) are reported in Fig. 3b.

TABLE I MEASUREMENT ERRORS AT DIFFERENT INCLINATIONS

Inclination	Mean AE (mean ± U[a]) [mL]	Mean RE (mean ± U[a]) [%]
70°	0.08[b] ± 0.04	2.1[b] ± 0.9
50°	0.19 ± 0.07	4.9 ± 1.7
30°	0.23 ± 0.04	5.7 ± 1.1

a. The reported uncertainty (U) is the *expanded uncertainty* calculated using a Student reference distribution and a level of confidence of 95%.

b. p<0.01 vs. 30° and 50° (One-way ANOVA or Kruskal-Wallis test on ranks, as appropriate, with Tukey-Kramer post hoc)

It must be considered that the resolution of the pipette used to take the liquid volume determines an uncertainty U_{ref} in the reference volume (4 mL), that is equal to 0.048 mL (calculated with a confidence level of 95%). Thus, this uncertainty implies a minimum AE in the measurements equal to 0.048 mL (see Fig. 3a) and a minimum RE of 1.2%.

One-way ANOVA, or the non-parametric Kruskal-Wallis test when appropriate, is performed with Tukey-Kramer post hoc test to verify the differences between errors at different tilt angles and it demonstrates that estimated volumes obtained at the highest inclination of 70° present lower AE than the others (p=0.0002), as reported by Table I.

The better volume estimation performances at higher inclinations are consistent with the algorithm definition which implies that a given error in the tilt angle (θ) estimate is more influential at lower inclinations.

In fact, following the algorithm defined in II.A, if an error (θ_{err}) occurs, it determinates an error (ΔV_{err}) in the volume estimation as well,

$$\Delta V_{err} = \Delta V_{\theta+\theta_{err}} - \Delta V_{\theta}. \quad (7)$$

Considering ΔV_{θ} equal to the subtracted volume

$$\Delta V_{\theta} = \frac{\Delta P \cdot S}{g\rho} \cdot \frac{1}{\sin\theta} = 4, \quad (8)$$

the error in the volume estimation can be expressed as follows,

$$\Delta V_{err} = 4 \cdot \left(\frac{\sin\theta}{\sin\theta + \theta_{err}} - 1 \right), \quad (9)$$

and it decreases with increasing tilt angle.

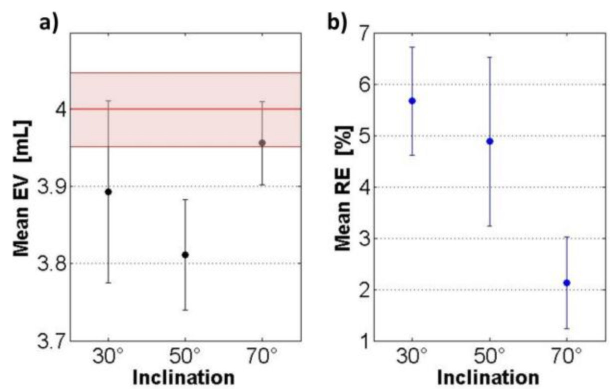

Fig. 3 a) Mean values of the Estimated Volumes (EV) with their uncertainty bars at 3 tilt angles of the reservoir. The red area marks the subtracted volume with its uncertainty U_{ref} due to the pipette resolution; b) Mean values of the Relative Errors (RE) and their uncertainty U at 3 tilt angles.

Furthermore the error values, expressed as the differences between the estimated and the subtracted volume, including the sign, can be analyzed in order to assess the presence or not of an under or over estimation of the volume, that could induce to reflect on the presence of a systematic error.

Fig. 4a reports the values of the volume errors obtained in all the measurements at the worst condition, i.e., at the lowest tilt angle of 30°. A systematic error is not observed since the mean value is not significantly different from zero, as demonstrated by the Wilcoxon signed-rank test (p>0.05), a non-parametric alternative to the t-test, as well as at the highest inclination of 70° (p>0.05). Fig. 4c shows how several measurements at 70° of inclination in fact fall within or strictly close to the minimum error range introduced by the pipette resolution.

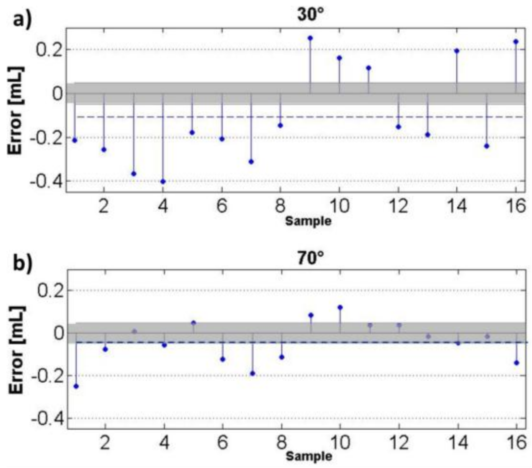

Fig. 4 Measurement errors, reported as the difference between the estimated volume and the subtracted volume (*Error=estimated volume–4mL*), are plotted separately for the lowest (a) and the highest (b) reservoir tilt angle (16 measurements each one). The blue dashed line marks the mean value, whereas the grey zone points out the minimum error (±0.048 mL) due to the pipette resolution.

III. Conclusion

Sucking is a complex and fundamental task for newborns and represents a possible marker of neurologic dysfunctions detectable since the first months of life. Sucking efficiency (SEF) is an important quantity to be monitored in order to assess the newborn's sucking pattern and its maturity. In this work a new ecological method for SEF monitoring has been introduced and experimentally validated. The proposed method allows to estimate the volume of liquid ingested by the newborn during a burst through a non-invasive measure of hydrostatic pressure exerted at the teat base. Integrating this methodology with an ecological measure of intraoral pressure [19] that provides the number of sucks per burst, it is possible to estimate the SEF (volume of ingested milk per suck).

The proposed method does not produce a systematic under or over estimation, however the measurement errors depend on the bottle inclination. The lowest errors are obtained for a high tilt angle (70°), when the RE in the estimation of the minimum volume of interest is within the 3%. However the method enables to estimate the same volume at the lowest likely inclination of the bottle (30°) with a RE within the 7%.

A future development of the implemented algorithm will be the inclusion of a method to take account of the milk or formula density which should be estimated as well, since it can be unknown and can actually vary from infant to infant. Furthermore a 9-axis magneto-inertial sensor will be integrated in the presented sensing core for a dynamic estimation of the bottle orientation. The final release of the electronics will be embedded on a custom-made feeding bottle to allow the screening of a large number of newborns through a common objective tool.

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