An Automatized System for the Assessment of Nutritive Sucking Behavior in Infants: a Preliminary Analysis on Term Neonates

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***Abstract*— Nutritive Sucking (NS) is a highly organized process that can reflect infants' maturation during the early post-natal period. The assessment of NS may provide a sensitive means of evaluating early motor skills and their development. Thus, a reliable tool for assessing sucking behavior may benefit diagnostics and treatment of newborns since the first days of life.**

The aim of this work is to propose an automatized system to measure sucking ability and calculate a set of objective and quantitative indices for its assessment. We focused on the analysis of the Intraoral Pressure (IP) generated by infants while feeding: an ad-hoc designed software application was developed to analyze the signal obtained by a pressure transducer connected with a catheter placed through a standard bottle teat into the oral cavity during feeding. Automatic algorithms for suck and burst identification and for their characterization are described.

We carried out a preliminary test of the system, analyzing data from two healthy term newborns, tested twice over time (1-2 days old and 6-10 weeks later). We calculated a set of different sucking parameters (e.g. sucking amplitude, frequency and area), and proposed some indices, that are typically used for the assessment of motor control, in order to assess the smoothness of IP. Results encourage further investigation of the proposed system for monitoring the development of early sucking skills.

I. INTRODUCTION

The assessment of infants' feeding competence is widely recognized as essential for discharge timing [1], and as a predictive indicator of developmental progress after discharge [2]. Moreover, neonatal sucking behavior can be viewed as a precocious motor skill, requiring the careful integration of different muscles via the central nervous system. Thus, it may also provide an early means of exploring mechanisms of fine motor control [3], and studying children neurodevelopment in a non-obtrusive way, as done for other motor tasks [4]-[5]. However, current methods for neonatal feeding assessment in clinical practice are often subjective, non-quantitative, and variable [1]. Thus, given the need of reliable objective measures [2], recent research focused on this, using different apparatuses for measurement, and different indices for the analysis of sucking behavior [6]. In particular, sucking skills in term infants may be assessed through the measurement of Intraoral Pressure (IP) [6]-[9]. However, few studies described the algorithms used to characterize the sucking signal and extract specific parameters from it [9]-[10].

The aim of the present paper is to address this issue: we propose an automatic computational system for the calculation of quantitative indices of sucking behavior. Further, we carried out a preliminary test of the proposed system with the IP traces obtained from two newborn infants, tested at birth and after two months. The long-term goal of the study is to develop a new tool to improve diagnostics, enable early treatment for newborns, and assist in the assessment of infant neurological and neuromotor health.

II. MATERIALS AND METHODS

A. Measuring Apparatus

Intra-oral pressure was measured using a pressure transducer (TranStar, Medex, UK/France/Italy/Germany), connected to a catheter primed with distilled water (40 cm in length, internal diameter of 1.0 mm; Vygon, France). The catheter was inserted through the teat (Standard Teat, Cow & Gate, UK) of a feeding bottle so that it protruded about 2 mm from its tip into the infant's oral cavity. Data, sampled at 100 Hz, were captured to a laptop PC using proprietary software (Collect4, General Electric Healthcare, Finland).

B. Data Acquisition

Pressure signals were acquired from two term-birth (born after 37 weeks of gestation), healthy infants (labeled as *s1* and *s2*). They were tested twice: the first test was carried out shortly after birth, at 1-2 days postnatal age (PNA), and the second one 6-10 weeks after.

C. Signal Analysis

IP is characterized by a pattern of bursts of sucks alternated with pauses [9]. Each suck is composed of an Increasing Suction (IS) phase, followed by a change in pressure in the opposite direction giving a Decreasing Suction (DS) phase [3]. The bandwidth of the pressure signal can be considered below 20 Hz according to previous results obtained from the analysis of the Power Spectral Density, reported in [12]. Thus, pressure signals have been low-pass filtered with a cut-off frequency equal to 20 Hz. The filtered signals have been given as input to the software system designed for the analysis.

The software application was designed to read pressure data files and identify the different components of a sucking pattern: sucks and bursts of sucks. A specialized peak picking algorithm was implemented for automatic suck identification, using both pressure and time criteria. First of all, the negative peaks exceeding a pressure threshold are detected. Then, two consecutive pressure peaks, exceeding such threshold, are counted as separate sucks if: i) the time interval between

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them exceeds a time threshold; and ii) the pressure variations (*ΔP*), with respect to the local maxima between the two peaks, exceed a pressure threshold (see Fig.1). Otherwise, the two deflections are considered as parts of a single sucking event, with the peak value corresponding to the highest of the two.

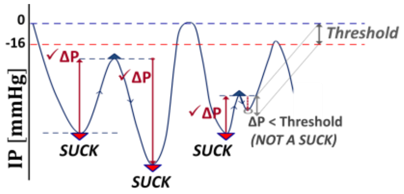

Figure 1. Suck detection algorithm: two consecutive peaks are marked as sucks (red triangles), if the pressure variations (ΔP) with respect to the local maxima (blue triangles) are greater than the threshold (16 mmHg).

These criteria were used to reject small fluctuations that do not correspond to suck events. We set a pressure threshold equal to -16 mmHg, and an inter-suck threshold equal to 0.3 s, according to literature values [8],[10]. The onset and the ending of a suck was detected finding out the local maximum between two consecutive sucks; however, if it was higher than zero, the zero-crossing points were taken as ending and onset of the two sucks. For a suck being the first or the last of a burst, the first maximum passing the threshold before or after the suck was marked as onset or ending, respectively.

Finally, an algorithm for burst and pause detection was implemented: a *pause* is identified as any period between sucking peaks lasting more than 3 s, and a *burst* as a group of at least 3 sucks bounded by pauses.

D. Indices Calculation

Once sucks and bursts are detected, the software proceeds with the calculation of a set of features characterizing the sucking pattern (see Fig. 2). The following indices, that are among the ones from literature [6], were calculated for each suck:

i. Sucking Amplitude (SkA), defined as the absolute value of the negative peak corresponding to a suck;

ii. Inter-Suck Width (ISkW), defined as the interval between two consecutive sucking peaks in a burst (sucking period);

iii. Sucking Frequency (SkF), defined as the inverse of the sucking period (1/ISkW);

iv. Suck Area (SkAr), defined as the integral of IP calculated between the onset and the end of a suck (see Fig. 3b).

We also considered some indices characterizing the two different phases of each suck, i.e., IS and DS (see Fig. 3a):

v. IS Duration (ISD), defined as the time interval between the onset and the peak of a suck;

vi. DS Duration (DSD), defined as the time interval between the peak and the end of a suck;

vii. IS Slope (ISS), the SkA divided by the ISD;

viii. DS Slope (DSS), defined as the SkA divided by the DSD.

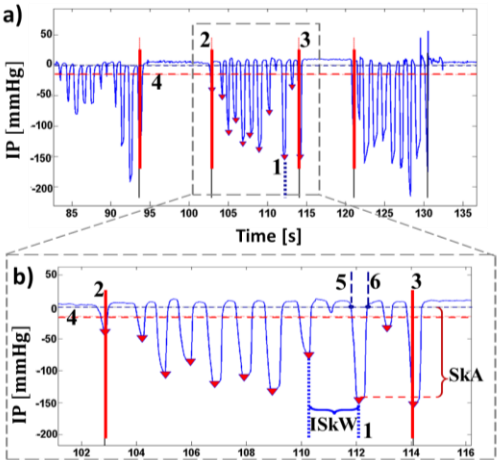

Figure 2. Analysis of a filtered IP signal. **a**) Suck and burst detection: 1.Detected sucks 2. Burst onset; 3. Burst end; 4. Threshold (i.e. -16 mmHg). **b**) Intra-burst characterization: 5. Suck onset; 6. Suck End; ISkW, Inter-Suck Width; SkA, Sucking Amplitude.

The ISD and DSD can be considered as measures of the duration of musculature activation and relaxation; whereas the ISS and DSS as measures of activation and relaxation intensity.

By controlling the motor coordination of different oral structures (see Fig. 3b), the infant modulates IP to optimize the flow of milk into the mouth first, and then to accumulate the expressed milk into the back of the mouth prior to swallowing [11]. For this reason, we also employed some indices typically used for the assessment of motor coordination and control, in order to enable improved sensitivity of developmental advance in analysis of the IP signal. If successful, these measures may improve sensitivity to neurological complication or neurodevelopmental health.

The speed profile of the IP (IPs) during each suck was calculated, in order to extract some *smoothness* measures. Movement smoothness in fact is a measure of motor performance, often based on the speed profile, that reflects also the neonate's motor development [13]. Hence, considering the IP changes as results of the movement of oral structures (Fig. 3b), we estimated the IP smoothness (η) separately for IS and DS phase. There is not a standard quantitative measure for movement smoothness [15], so we used two different metrics:

ix. Peaks metric (η_p): the number of local maxima in the speed profile (Fig. 3c) [14]: the lower its value, the higher the smoothness;

x. Spectral arc length metric (η_{sal}): the arc length of the amplitude- and frequency-normalized Fourier magnitude spectrum of the speed profile (Fig. 3d), as defined in [15]: the lower its value, the higher the smoothness;

The η_p is one of the most commonly used smoothness measures for motor control [14], while η_{sal} has recently been proposed as a valid and consistent measure sensitive to modifications in motor behavior and robust to measurement noise [15].

E. *Data Analysis*

The previously described set of variables was calculated for each detected suck for each subject (sporadic sucks, not being part of a burst, were not considered for the analysis). We considered for the analysis at most the first five minutes of recording starting from the first burst, in order to avoid the effect of fatigue, as suggested in literature [8]. Thus, for each subject, we had a number of observations equal to the number of sucks in bursts identified by the implemented algorithms.

Subjects were tested at two different ages, and the effect of the *Age* factor was tested on each dependent variable. We will refer to the two age levels as *Age 1* (1-2 days PNA) and *Age 2* (6-10 weeks after). For each *Age* level, we also compared the values of each variable between *s1* and *s2*, to verify if the two samples are from identical continuous distributions with equal medians; in the case it was not verified, the *Age* effect was tested separately in the two subjects. Comparisons were performed by a Wilcoxon rank sum test (i.e, the non-parametric alternative to the independent *t*-test), which is robust to outliers and does not require normal distribution of the data.

Wilcoxon matched-pairs signed rank tests were used to compare IS and DS within a suck at the two different levels of age (considering both infants), in order to investigate if and how the two suction phases differ at different ages, in terms of ISD, DSD, ISS and DSS.

For all tests, p-values <0.05 were considered significant. Data central values will be reported as median (interquartile range: 25th, 75th percentile).

III. RESULTS AND DISCUSSION

A total number of 743 sucks in 23 bursts was detected from the four pressure traces (221 sucks in 11 bursts from s1, and 522 in 12 bursts from s2). Each detected suck was characterized by the previously described indices.

Results of the analysis revealed that ISkW, SkF and SkA significantly changed with a trend compliant with previous literature on term infants' normal development.

The ISkW significantly shortens in both subjects over time (p<0.001), passing from 1.2 to 1 s in s1, and from 0.8 to 0.7 s in s2 (Fig. 4a). A correlated significant increase in SkF was observed (p<0.001). This result corresponds with what we expected according to previous studies investigating the development of term newborns over the postnatal period [16]. Moreover, this trend appeared to be characteristic of infants' development also beyond the neonatal period as reported in [10].

Sucking amplitude significantly increases with age (Fig. 4b), passing from 75 (52,115) mmHg at Age 1 to 133 (99, 165) mmHg at Age 2 (p<0.001). The test was performed on the entire sample as no differences resulted between subjects at the two ages. This suggests that an increase in suction strength, measured through SkA, is characteristic of the very early postnatal development, according to the results from previous studies [8]-[10]. Besides, we analyzed the trend of SkA over a single session, to test the concordance with results of Lang et al. [9], who reported a significant decrease of SkA while feeding during the first days after birth, probably imputable to increasing fatigue. Our results confirmed this trend: we observed a significant decrease in SkA during the first minute of feeding, compared to the minutes after (Wilcoxon rank sum test, p<0.05) in both subjects.

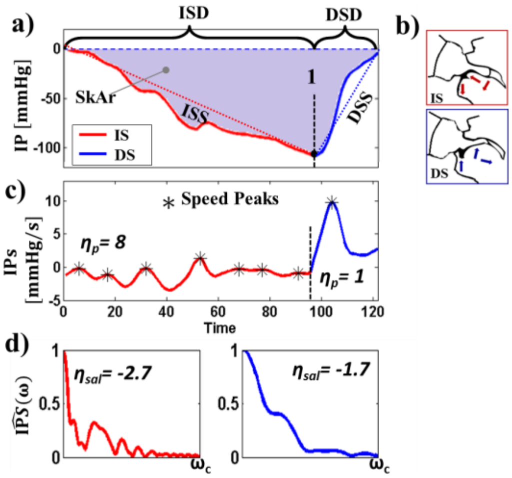

Figure 3. Analysis of the Increasing and Decreasing Suction phases. **a)** IP during a suck is charaterized by: Sucking Area (SkAr, grey area); IS Duration (ISD) between the suck onset and peak (1); DS Duration (DSD), between the suck peak (1) and ending; IS and a DS slope (red and blue dotted line). **b)** Movements during IS and DS phase: during IS, the tongue moves forward and down as the jaw is lowered; during DS, the tongue moves upwards and backwards as the jaw is raised. **c)** IP speed profile (IPs) of IS (red) and DS (blue): DS is smoother than IS (η_p: 1 vs. 8). **d)** IP speed normalized spectrum of IS and DS, and the respective values of spectral arc length (η_{sal}).

The analysis of the other indices we proposed (SkAr, ISD, DSD, ISS, DSS, IS- and DS- η) suggests the presence of developmental characteristics not yet investigated for characterizing the normal development of infants.

The index SkAr had been previously investigated to consider postnatal development beyond the neonatal period, but it showed high inter-subject variability and a low age effect [10]. In contrast, we observed SkAr significantly increased between neonatal (Age 1) and postnatal (Age 2) stages in both infants tested (p<0.01) (Fig 4c). These preliminary findings suggest this index may be more sensitive in early development and could be exploited for neonatal and postnatal assessment. We suggest SkAr is a potentially interesting feature that requires future investigation.

Results from analysis of pressure speed profiles suggest smoothness improves, *i.e.* increases, with age in term infants. At the two ages, *s1* and *s2* did not show inter-subject differences in IS smoothness as measured through η_{sal} (though not in terms of η_p, whose values at each age were dependent on the subject). Thus, the age effect was tested on the entire sample. A significant increase in IS smoothness with age is apparent: η_{sal} increased from -2 (-2.4,-1.8) to -1.8 (-1.9,-1.7) (p<0.001). The development of DS smoothness, on the other hand, differed between the two subjects.

Further, paired comparisons between the two different phases of suction, revealed some significant differences that change with age. The IS is significantly longer than DS at Age 1 (ISD: 0.36 s (0.28, 0.75); DSD: 0.2 s (0.17, 0.27); p<0.001), while this difference is absent at Age 2, when the value of duration of the two phases is 0.31 s. A difference also emerged from the comparison of IS and DS slopes: at *Age 1* the activation phase is less intense than relaxation (ISS is significantly lower than DSS: 377 vs. 451 mmHg/s, p<0.001); while at *Age 2* this difference is brought down, and the value of intensity of the two phases is 468 mmHg/s. These results suggest a development in the activation-relaxation pattern of suction musculature: in particular, it appears that musculature activation (IS) develops over the first weeks of life to reach the level of the DS, in terms of smoothness and duration.

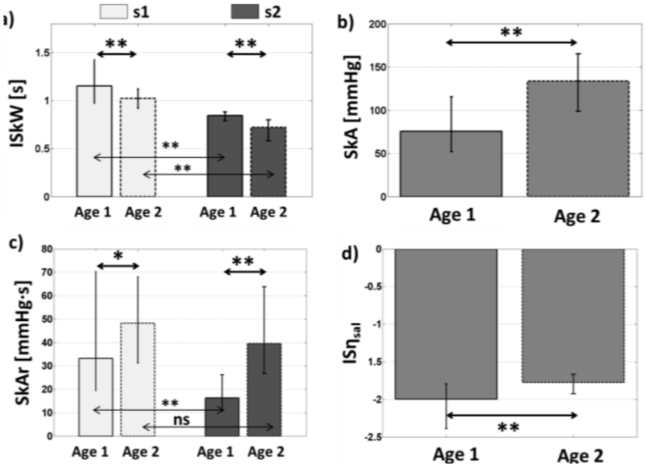

Figure 4. Statistical results on different sucking indices across the two ages (Wilcoxon rank sum test, *, p<0.01, ** p<0.001). a) Decreasing ISkW in both subjects; b) Increasing SkA (results on the entire sample, as no inter-subect differences occur); c) Increasing SkAr in both subjects; d) Increasing smoothness (η_{sal}) of IS (results on the entire sample, as no inter-subect differences occur).

IV. CONCLUSIONS

The proposed automatized system allowed measurement and analysis of IP generated by newborns while feeding from a bottle. Algorithms for suck and burst detection have been presented and tested on a sample of pressure traces recorded from healthy infants born at term.

The analysis of SkA and IskW, as calculated by the system, demonstrated typical developmental features of sucking behavior over the first weeks of life. Confirmation of the results from these parameters represents a first step to evaluate the validity of the proposed system.

Moreover, novel indices for IP analysis proposed and calculated through our automatic system (sucking area, IS- and DS- duration and intensity, and IS smoothness) appeared to characterize development in healthy infants' sucking behavior. Further investigation is now required on a greater sample of infants and must consider other independent factors (e.g. prematurity or weight). Further, application of a smoothness index for IP signals is encouraged: it may be an important index to consider, especially given its importance in other motor modalities [11].

In conclusion, we described an automatic system for the calculation of quantitative indices of sucking behavior from IP signals. Preliminary results suggest that this system may be further explored as a possible pathway to objectively assess early sucking skills in neonates for the early assessment of development and health.

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