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Automatic ultrasound technique to measure angle of progression during labor

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KEYWORDS: childbirth; intrapartum ultrasound; labor monitoring; medical decision support; progression angle; ultrasonic imaging

ABSTRACT

Objective *To evaluate the accuracy and reliability of an automatic ultrasound technique for assessment of the angle of progression (AoP) during labor.*

Methods *Thirty-nine pregnant women in the second stage of labor, with fetus in cephalic presentation, underwent conventional labor management with additional translabial sonographic examination. AoP was measured in a total of 95 acquisition sessions, both automatically by an innovative algorithm and manually by an experienced sonographer, who was blinded to the algorithm outcome. The results obtained from the manual measurement were used as the reference against which the performance of the algorithm was assessed. In order to overcome the common difficulties encountered when visualizing by sonography the pubic symphysis, the AoP was measured by considering as the symphysis landmark its centroid rather than its distal point, thereby assuring high measurement reliability and reproducibility, while maintaining objectivity and accuracy in the evaluation of progression of labor.*

Results *There was a strong and statistically significant correlation between AoP values measured by the algorithm and the reference values ($r = 0.99$, $P < 0.001$). The high accuracy provided by the automatic method was also highlighted by the corresponding high values of the coefficient of determination ($r^2 = 0.98$) and the low residual errors (root mean square error = 2°27′ (2.1%)). The global agreement between the two methods, assessed through Bland–Altman analysis, resulted in a negligible mean difference of 1°1′ (limits of agreement, 4°29′).*

Conclusions *The proposed automatic algorithm is a reliable technique for measurement of the AoP. Its (relative) operator-independence has the potential to reduce human errors and speed up ultrasound acquisition time, which should facilitate management of women during labor. Copyright © 2017 ISUOG. Published by John Wiley & Sons Ltd.*

INTRODUCTION

Intrapartum assessment of progress of labor is currently performed through subjective and invasive transvaginal manual inspection, the inaccuracy of which has been reported widely in the literature[1–6]. Scientific evidence indicates that manual examinations are affected by high error rates (up to 88% of cases) in the determination of labor progression parameters such as fetal head station, cervical dilatation and fetal head position[2,6–10]. The management of labor and childbirth therefore needs new approaches and guidelines on which to rely, with objective indications for standardized quantitative monitoring and appropriate medical decision-making to enable early identification of the most appropriate mode of delivery.

Recent publications have demonstrated the role of ultrasound techniques in the measurement of parameters indicative of the progress of labor[8,11–18]. For instance, evaluation of the 'angle of progression' (AoP) by transperineal ultrasound provides an objective, accurate and reproducible method for determining fetal head progression during labor[14,19]. Estimation of AoP could also be useful for the management of term pregnancies[8,20] and for predicting the mode of delivery[15,21]. Nevertheless, routine employment of these methods is hindered by a lack of fully automatic and objective approaches giving real-time support to clinical decisions.

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In this context, a real-time tracking algorithm for non-invasive and automatic monitoring of AoP during the second stage of labor was developed by our research group and tested preliminarily on both a birth simulator and a small number of parturients[22,23]. The aim of the present study was to introduce an improved version of our algorithm and to evaluate its accuracy in a routine clinical context.

METHODS

Patients

The study was conducted at the Department of Obstetrics and Gynecology of 'Santa Caterina Novella' Hospital, in Galatina, Lecce, Italy, and included all patients fulfilling the following enrolment criteria: singleton pregnancy at term gestation (37 weeks or more), fetus in cephalic presentation, in the second stage of labor, absence of documented fetal malformations, no previous Cesarean section, no contraindications to vaginal birth, uncomplicated pregnancy and absence of severe maternal obesity. Parturients were recruited over the 2-month period from 1 February to 31 March 2016 and all of them received conventional labor management, according to standard local procedures. Additional translabial sonographic acquisitions were performed after a uterine contraction, as detailed below. The type of delivery of each patient was recorded in our database for a preliminary study of possible correlations between values of sonographically measured parameters and mode of delivery. The study protocol was approved by the hospital ethics committee and all patients gave informed written consent to participate.

Ultrasound system and acquisitions

Ultrasound acquisitions were performed employing the 'SensUS Touch' system (Amolab Srl, Lecce, Italy; www.amolab.it), a sonographic device consisting of a tablet personal computer equipped with a convex transducer operating at the nominal frequency of 3.5 MHz. The device was provided in an 'open' configuration for research purposes, specifically allowing the possibility of integrating our novel software algorithm dedicated to real-time monitoring of labor through fully automated calculation of the AoP from intrapartum ultrasound images. However, for the present observational study, in order to avoid any possible interference with labor management decisions, the real-time image analysis was disabled and replaced by offline processing of the acquired images.

Each parturient underwent a series of translabial sonographic acquisitions at different fetal head stations. All acquisitions were performed during the second stage of labor, within 1 min after the peak intensity of a uterine contraction. The first sonographic scan was performed as soon as the patient entered the labor room (typically, but not necessarily, at the beginning of the second stage); therefore, the total number of sonographic acquisitions performed on a patient depended on the fetal head station at the time of the first acquisition and the total duration of the second stage of labor. The time interval between successive sonographic acquisitions varied and was always established by the clinical staff, whose aim was to monitor fetal head progression sonographically; an ultrasound acquisition was performed each time the clinician needed to visualize the fetal head progression.

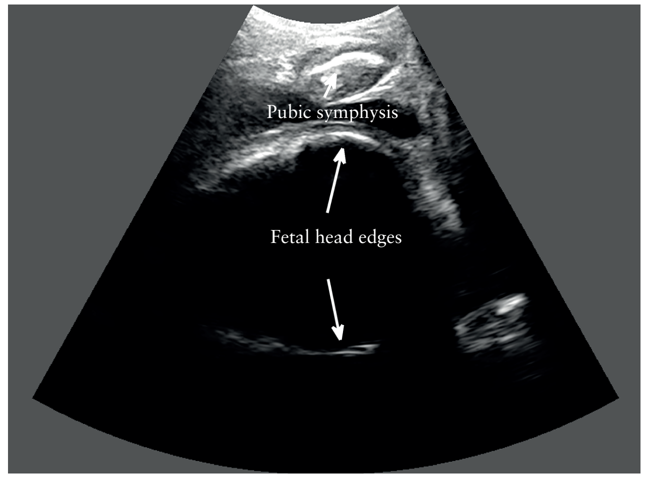

Figure 1 Typical B-mode ultrasound image acquired translabially during second stage of labor: pubic symphysis and fetal head edges are seen in upper part and in central part of image, respectively.

For each acquisition, the operator placed the probe longitudinally in the translabial area, aiming to visualize simultaneously the pubic symphysis horizontally in the upper central part of the image and the edges of the fetal head in the lower part (Figure 1). In order to facilitate this process for the operator, an ellipsoidal guide for the correct positioning of the pubic symphysis in the sonographic field of view was also displayed on the system's interface. Once correct visualization was achieved, the operator started a 5-s acquisition: 100 B-mode images were acquired (frame rate, ~20 frames/s) and stored for subsequent offline analysis, in which each ultrasound image was analyzed by the automatic algorithm. The results provided by the automatic algorithm were then compared with those obtained through manual identification (i.e. segmentation) of the reference anatomical landmark structures, performed on a single representative image (reference image) selected for manual analysis during postprocessing by the experienced sonographer, who was blinded to the algorithm outcome. It should be noted that, for each patient, the images from the first acquisition session were processed through an automatic segmentation algorithm, whereas a different algorithm based on automatic pattern tracking was employed for subsequent sessions, in order to optimize computational resources and calculation times. Both algorithms were fully automatic and for each session all 100 acquired images were processed, one of these being selected for the manual analysis (reference image).

Angle of progression: definition and preliminary studies

According to Barbera *et al.*[14], the AoP is defined as the angle between the longitudinal axis of the pubic symphysis and the line running from the anterior edge of the pubic symphysis tangentially to the leading edge of the fetal skull. In the present study, in order to increase reliability and reproducibility, AoP measurements were obtained using the centroid of the pubic symphysis rather than its distal point as the symphysis landmark, since this is a more stable marker that is more easily detected. Thus, the resulting AoP was the angle between the longitudinal axis of the pubic symphysis and the line running from its centroid tangentially to the leading edge of the fetal skull. Technically, the centroid is defined as the point corresponding to the 'center of mass' of the pubic symphysis and can be identified analytically through a calculation that takes into account the locations of single symphysis pixels and their intensity values. From a practical point of view, the centroid can be identified by an operator easily, and with optimal accuracy, as the center of symmetry of the brightest symphysis area on the image. In our case, the choice of adopting the centroid rather than the distal point as an anatomical landmark was based on two factors: (1) the difficulty encountered commonly by the operator in visualizing correctly the anterior edge of the pubic symphysis in acquired images, which limits reliability and reproducibility of AoP measurements; and (2) the fact that, in order to implement a fully automatic algorithm for AoP calculations, characterized by high reproducibility, the centroid represents a better option than the distal point, since it is always located in an easily detectable highly echogenic bone area, whereas the distal point, located on the symphysis border, often presents a gray-level value very close to the background noise. Figure 2 shows an example of a typical B-mode ultrasound image in which the distal point of the pubic symphysis is not clearly visible, whereas the centroid is detectable with a good level of confidence through the procedures described above.

The ease of detection of the centroid was verified through a dedicated preliminary study conducted on 10 volunteers who satisfied the same enrolment criteria as those used for the study group. An experienced sonographer acquired three translabial ultrasound images from each volunteer, corresponding to three different fetal head stations, giving a total of 30 different images. Five identical copies of each image were produced and the resulting 150 images were ordered in a random sequence. A second experienced sonographer was asked to mark on each image the symphysis centroid and distal point, or to declare that one or both of these points was not visible in the image. For each group of five identical images, the averages of the five centroid and of the five distal point positions were calculated, assuming these to be good approximations of the true positions of the points. The distance between each single marked point and the corresponding average point was calculated, and the single points whose distance was < 2 mm from the

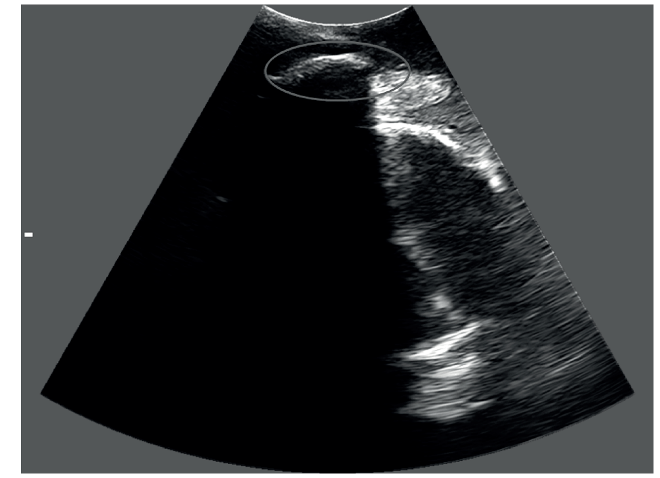

Figure 2 Typical B-mode ultrasound image acquired translabially during second stage of labor, in which pubic symphysis distal point is not clearly visible and pubic symphysis centroid is detectable with good confidence using procedure described in text. Ellipsoidal guide for correct placement of symphysis within the image is also shown.

average were labeled as 'correctly identified'. For each set of five identical images, the mean distance between the single marked points and the corresponding average point was assumed as a measure of the reproducibility of point identification.

It is important to emphasize that the decision to select the pubic symphysis centroid as a marker should not affect the accuracy of monitoring of progression of labor, because this is assessed through the temporal evolution of successive AoP values, regardless of the values themselves.

Ultrasound data analysis for calculation of angle of progression

The offline analyses of acquired images were conducted using a fully automatic algorithm, which exploited a combination of morphological filters and pattern recognition methods to identify the pubic symphysis and the fetal head and to calculate the AoP. It is important to specify that neither manual corrections nor human input of any kind were applied in any step of the automatic algorithm calculations.

Algorithm working principle

The schematic illustration of the algorithm working principle is shown in Figure 3. Each acquisition session, consisting of a sequence of 100 frames acquired in a 5-s period, was processed through the following steps:

1. *Preliminary image validation*, based on gray level and geometrical feature analysis, in order to verify the image's suitability for the subsequent processing steps and to discard images of insufficient quality.
2. *Search for raw bone structures*, based only on pixel cluster positions and their gray value intensities. The term 'raw' indicates that this first attempt of

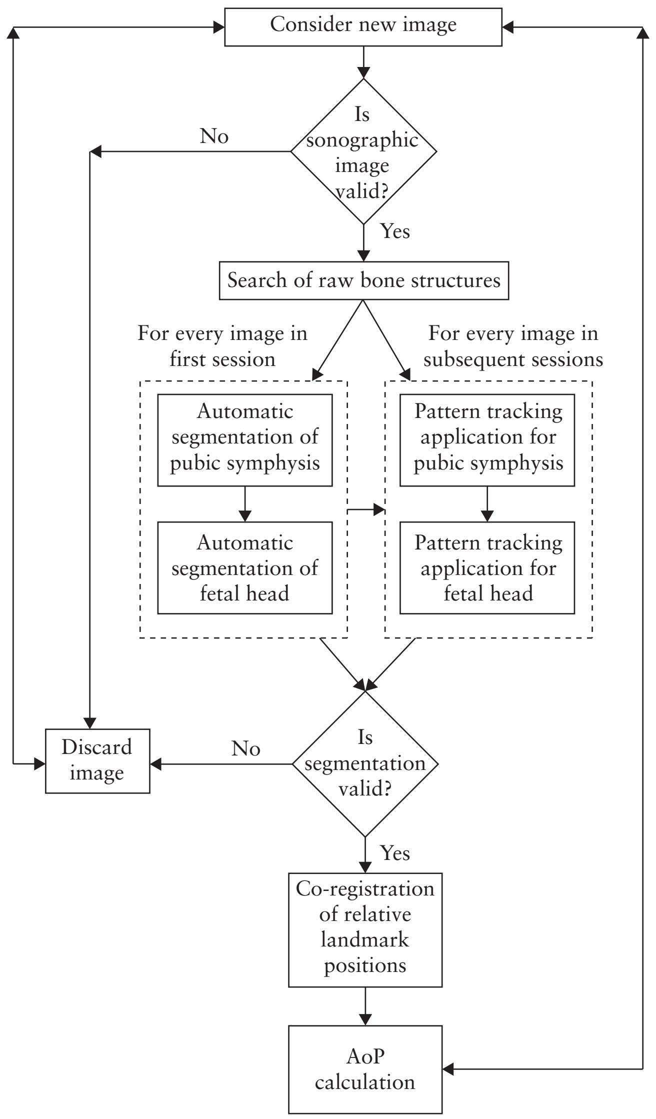

Figure 3 Schematic illustration of algorithm for fully automatic identification of pubic symphysis and fetal head and calculation of angle of progression (AoP) during labor. Pixel patterns corresponding to landmark structures identified in first acquisition session were used as references for pattern-tracking algorithm to identify these structures in subsequent acquisition sessions.

marker segmentation could be somewhat inaccurate because the pixel clusters identified may contain some imperfections due to background noise.

3. *Pubic symphysis and fetal head detection*, based either on morphological filters for automatic identification of the landmark bone structures (images from first acquisition session) or pattern tracking methods (images from subsequent acquisition sessions).
4. *Co-registration of coordinates for pubic symphysis and fetal head*, aimed at the knowledge of the relative position of the identified markers.
5. *AoP calculation*, adopting the definition of AoP specified above.

Once this process had been applied to all 100 images belonging to a particular acquisition session, the results were used to identify a single image representative of the whole session (reference image, to be used for manual segmentation). The image selected was the one whose associated parameters (AoP, symphysis centroid coordinates, fetal head center coordinates, fetal head radius) were closest to the corresponding average values.

Automatic identification of landmark bone structures

For each image in an acquisition session, the algorithm achieved fully automatic identification of the bone structures through the steps reported below. In particular, a custom-developed automatic segmentation approach was applied to the images of the first acquisition session, while a pattern tracking algorithm was implemented for the images from subsequent acquisition sessions, in order to optimize computational resources and calculation times.

Automatic segmentation

Automatic segmentation, summarized below, was applied only to the images of the first acquisition session. Full details of each step are given in Appendix S1.

1. *Bone-structure detection*. Bone-structure landmarks (pubic symphysis and fetal head) were first identified in a preliminary manner, according to their position in the ultrasound image and their pixel intensities. The image was then converted into a binary map (Figures 4a and 5a,b).
2. *Pubic symphysis segmentation*.
   I. *Median filter application* (Figure 4b);
   II. *Morphological evaluation*, including selective thresholding based on geometrical distribution of white pixel clusters (Figure 4b);
   III. *Structure hole-filling* (Figure 4c), this morphological operation performs the 'hole-filling' for the identified marker, ensuring that all pubic symphysis pixels that were erroneously excluded from the reference structure in previous steps are now correctly identified as being part of the identified marker;
   IV. *Centroid detection*, using original ultrasound image masked by the obtained binary map (Figure 4d);
   V. *Longitudinal axis detection*, through morphological evaluation of the segmented pubic symphysis (Figure 4d).
3. *Pubic symphysis validity check*, based on global geometric considerations related to symphysis longitudinal axis orientation and possibly undetected pubic symphysis parts.
4. *Fetal head segmentation*.
   I. *Median filter application* (Figure 5c,d);
   II. *Morphological evaluation* (Figure 5c,d);
   III. *Structure hole-filling* (Figure 5e,f);
   IV. *Merging of fetal head structures* (Figure 5g);
   V. *Detection of fetal head radius and center coordinates*, by selecting only identified pixels that optimize fitting of the leading edge of the fetal head with a circumference (Figure 5h).

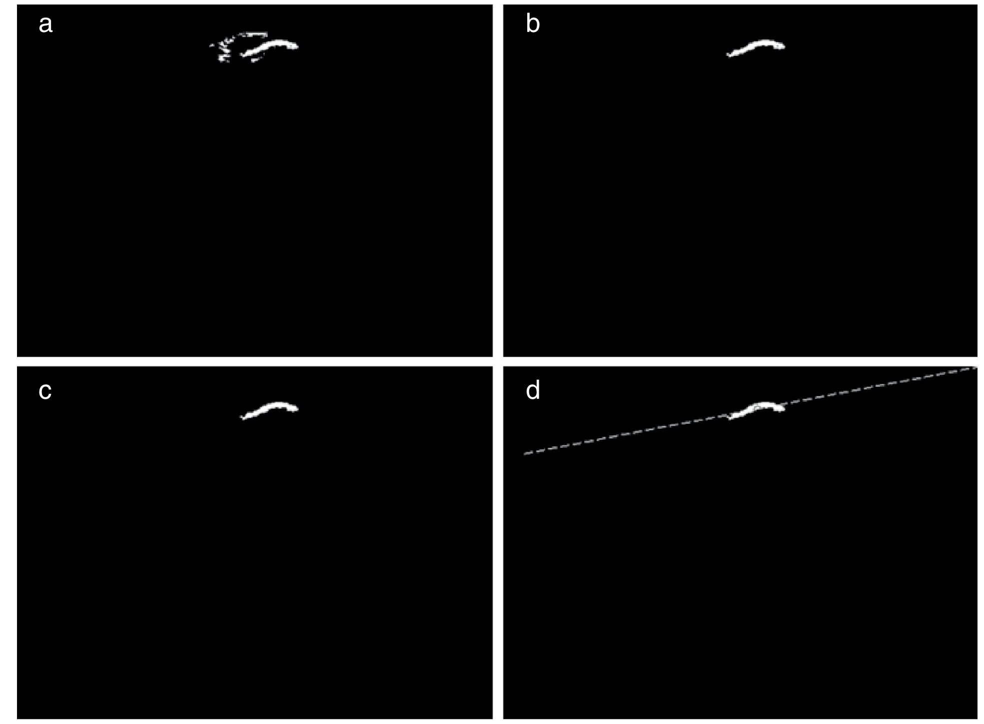

Figure 4 Application of processing steps for automatic identification of pubic symphysis in typical ultrasound image frame: (a) 'raw' identification of symphysis, according to pixel position in image and to their gray-level values, and conversion to a binary map; (b) median filter application and morphological evaluation; (c) structure hole-filling; (d) detection of pubic symphysis centroid and longitudinal axis (see Appendix S1 for details).

5. *Fetal head validity check*, based on geometric considerations, pixel gray-level intensity values inside identified structures and analysis of fetal head position.

Once this process had been repeated until all 100 images belonging to the first acquisition session of a particular patient had been analyzed, the algorithm evaluated the relative position of the identified landmark structures (i.e. pubic symphysis centroid and fetal head) and calculated the AoP value of that session. The pixel patterns corresponding to the landmark structures identified in the first acquisition session were then used as reference for the pattern-tracking algorithm employed to identify the landmark structures in subsequent acquisition sessions, as described below.

Figures 4 and 5 illustrate how the automatic segmentation steps would be applied to the image in Figure 1 in order to identify the longitudinal axis and centroid of the pubic symphysis (Figure 4) and the profile tracts corresponding to the fetal head (Figure 5). The final output of the process is shown in Figure 6.

Pattern tracking

Pattern tracking was applied only to images of acquisition sessions subsequent to the first session. Full details are given in Appendix S2.

1. *Pubic symphysis identification*.
   I. *Selection of pubic symphysis candidates*, considering all pixel clusters inside the ellipsoidal guide and above a specific threshold, which was optimized based on the intensity values of pixels belonging to the pubic symphysis segmented in the first acquisition session;
   II. *Feature extraction from pubic symphysis candidates*, providing useful attributes to characterize each candidate;
   III. *Classification of pubic symphysis candidates*, by searching among them for the set of features that minimized the difference with respect to the set of reference features extracted from the pubic symphysis segmented automatically in the first acquisition session.

Once the pubic symphysis was identified by the pattern tracking method, the algorithm extracted its weighted centroid and its longitudinal axis orientation following steps 2-IV and 2-V of the automatic segmentation algorithm, above.

2. *Fetal head identification*.
   I. *Selection of fetal head-structure candidates*, considering all pixel clusters within fixed image bands, through/in which the fetal head progresses during labor, and above a specific optimized threshold, which was again defined by exploiting the intensity values of the pixels belonging to the structures segmented in the first acquisition session;
   II. *Feature extraction from fetal head-structure candidates*;
   III. *Classification of fetal head-structure candidates*.

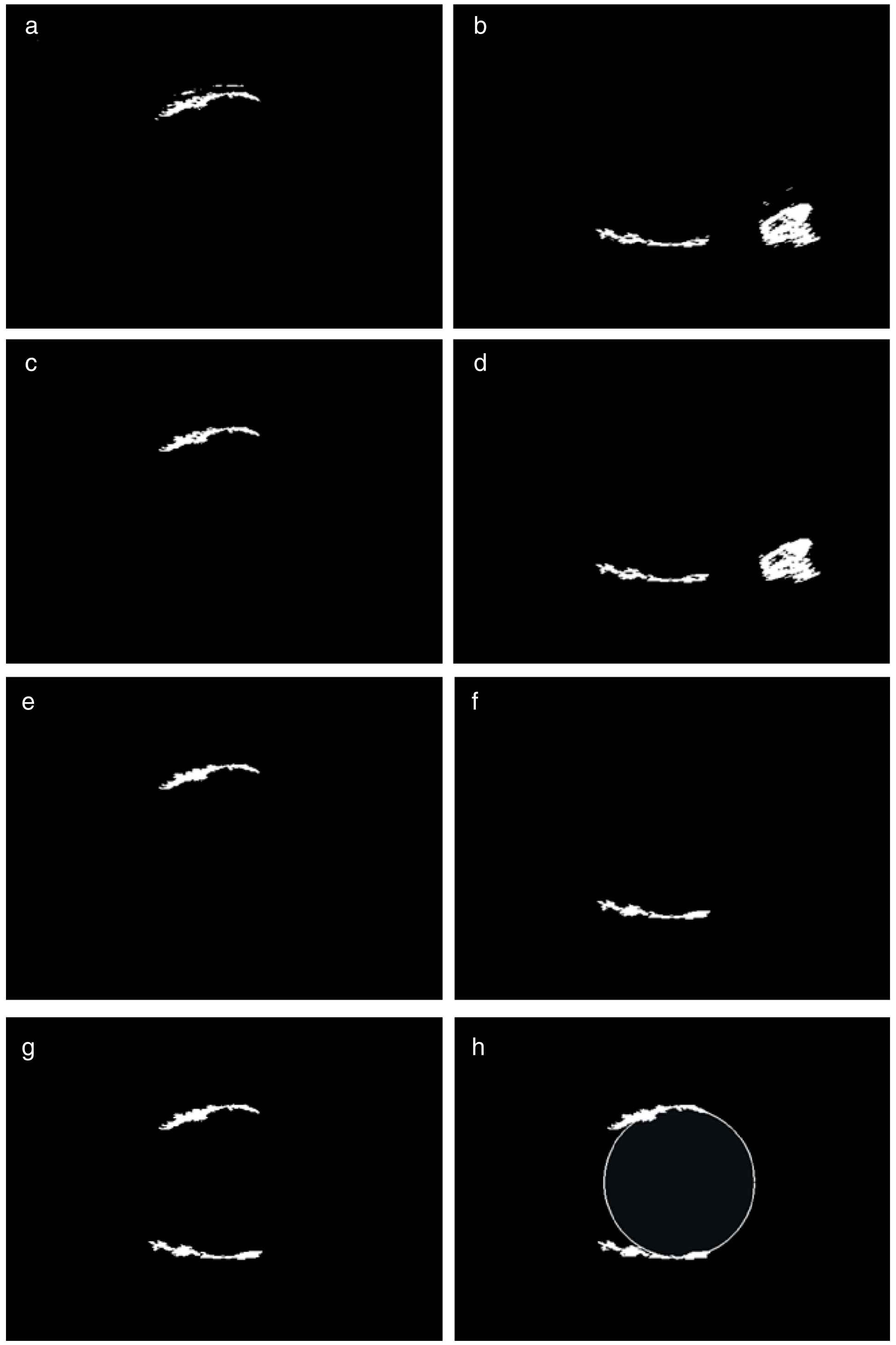

Figure 5 Application of processing steps for automatic identification of fetal head in typical ultrasound image frame: (a,b) 'raw' identification of fetal head upper (a) and lower (b) structures, according to pixel position in image and to their gray-level values, and conversion to a binary map; (c,d) median filter application and morphological evaluation on fetal head upper (c) and lower (d) structures; (e,f) hole-filling for fetal head upper (e) and lower (f) structures; (g) merging of fetal head structures; (h) determination of fetal head center and radius (see Appendix S1 for details).

Once the fetal head was identified by the pattern tracking method, the algorithm determined the radius and center coordinates of the corresponding fitting circumference by following step 4-V of the automatic segmentation algorithm, above.

Data analyses were performed on a modern personal computer equipped with an Intel i7 Core™ i7-3610QM processor at 2.3 GHz (8 GB of RAM, 64 bits); the analysis of a single patient's acquisition, including fully automatic identification of the target anatomical landmarks and AoP

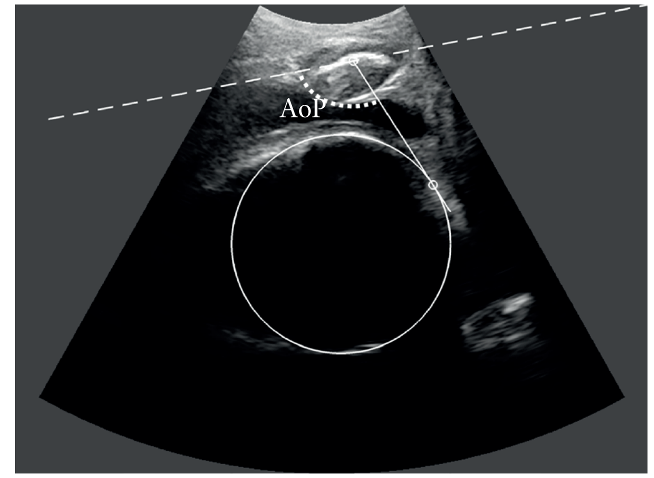

Figure 6 Automatic segmentation of typical transperineal ultrasound image and corresponding calculation of angle of progression (AoP) of fetal head during second stage of labor.

value calculation, took about 12 s for the first session and about 8 s for each subsequent session analysis, indicating pattern tracking to be the faster of these two approaches.

Statistical analysis

The accuracy of the proposed automatic algorithm was assessed by comparing these AoP values with those resulting from manual segmentation of the same images by an experienced operator (used as the reference). The correlation between AoP values was assessed through calculation of Pearson's correlation coefficient (r), the coefficient of determination (r^2) and the root mean square error (RMSE). Furthermore, agreement between the two methods of measuring AoP values was also evaluated, as recommended by Altman and Bland[24], by calculating the paired difference for each measurement and by estimating the bias and 95% limits of agreement relative to the average measurement of both methods.

RESULTS

Pubic symphysis centroid as reference marker

Our preliminary study confirmed that the pubic symphysis centroid is more easily and more reproducibly detectable than is the distal point of the symphysis. An experienced sonographer declared that the distal point of the symphysis was not clearly visible in 40 of the 150 (26.7%) images analyzed, while in the same images he always marked the centroid (150/150, 100.0%). The point specified was determined to be 'correctly identified' for all 150 (100%) of the centroids marked and for 72.7% (80/110) of the distal points. Therefore, the overall accuracy of identification of the distal point of the pubic symphysis was 53.3% (80/150) compared with 100.0% (150/150) for the centroid.

The observed average distance between single marked points and the corresponding average point, assumed to be the true location of the point, was 0.8 ± 0.4 mm for the symphysis centroid and 1.4 ± 0.9 mm for the distal point, providing a quantitative measure of the higher reproducibility of centroid detection.

Automatic measurement of angle of progression

A group of 39 parturients was recruited for the main study. In total, 95 sonographic acquisition sessions were collected: 19 parturients each underwent three sonographic acquisition sessions and 18 underwent two sessions, while only two parturients underwent a single acquisition session (because delivery followed soon after). The average duration of labor monitoring was approximately 1 h, although this was strongly dependent on the total duration of the second stage and the status of labor progression when monitoring started. The proposed method was totally non-invasive, did not create any discomfort for the pregnant women and the sonographic acquisitions were of short duration; as a result, the method was well tolerated by all patients. There was no case in which uncontrolled movements of the parturient during acquisition caused malfunction of the algorithm. Furthermore, the use of intrapartum ultrasound sometimes provided a psychological benefit, giving parturients the impression that they were receiving more complete and advanced monitoring of the progression of labor.

There was a strong and statistically significant correlation between the AoP values measured by the automatic algorithm and those obtained by the expert manual segmentation: $r = 0.99$ ($P < 0.001$). The high accuracy provided by the automatic method is also emphasized by the corresponding high values of the coefficient of determination ($r^2 = 0.98$) and the low residual errors: RMSE = $2°27'$ (2.1%). Figure 7 shows the scatterplot of the AoP measurements provided by the two different techniques, together with the line of equality (Pearson's correlation coefficient, $r = 0.99$). The corresponding Bland–Altman plot is given in Figure 8: the overall average difference in AoP measurement (expressed as bias ± 2 SD) was $1°1' \pm 4°29'$, further confirming the optimal agreement between the two methods.

Correlation between angle of progression and mode of delivery

Delivery was natural in all parturients whose measured AoP, determined automatically and confirmed through the expert manual analysis of the images, was > 137°. It is interesting to note that this finding is consistent with that of previous reports[14,25], taking into account the offset of the AoP measured from the centroid rather than from the edge of the pubic symphysis.

DISCUSSION

The recent literature includes reports on many sonographic approaches dedicated to quantitative monitoring of labor[25–31]. However, their routine clinical application is typically hindered, either by the necessity for significant

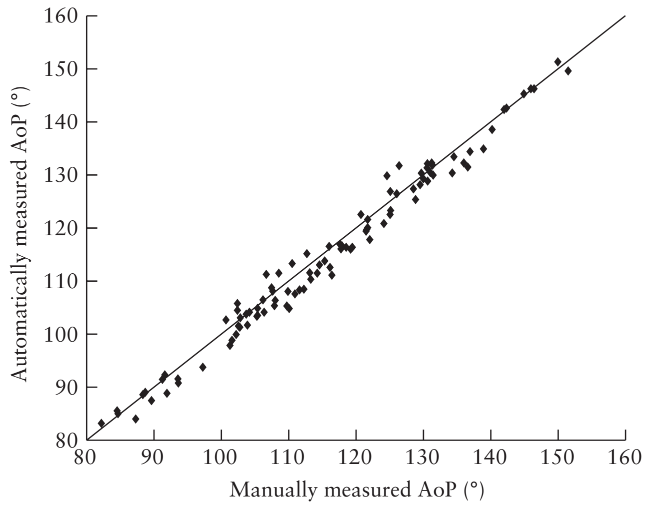

Figure 7 Scatterplot of angle-of-progression (AoP) values provided by manual and by automatic segmentation. Line of equality is shown. Global Pearson's correlation coefficient, $r = 0.99$.

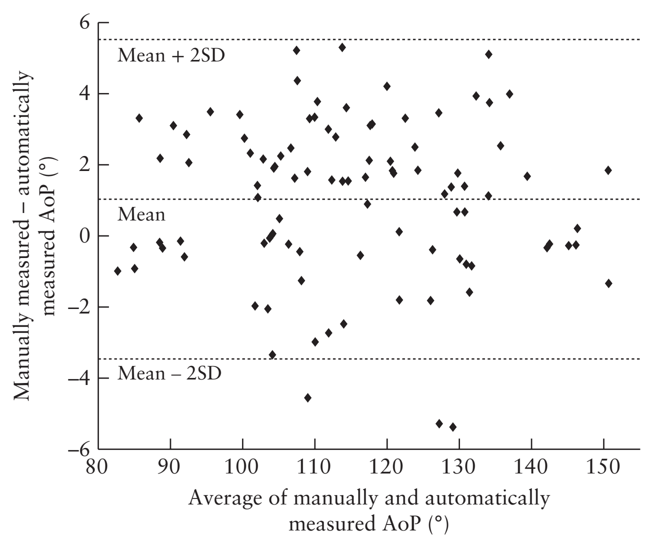

Figure 8 Bland–Altman plot for comparison of angle of progression (AoP) measured manually with those measured automatically.

operator–machine interaction, or by the invasiveness associated with the employment of specific devices, which can cause discomfort for the patient and risk of lesion or infection[32].

In this study we have introduced a new methodology for quantitative, automatic AoP measurement for monitoring the progress of labor. An automatic segmentation and tracking algorithm was used to identify reference landmarks and to evaluate fetal head progression during the second stage of labor. Validation was conducted on 95 sonographic acquisition sessions, evaluating the algorithm's results in comparison to manual contouring performed by an experienced operator. We found a strong and statistically significant correlation between the AoP values obtained by the two methods.

An important aspect of this study, in order to assure measurement reproducibility and reliability, was our decision to consider as a landmark the pubic symphysis centroid rather than its distal point. The usefulness and feasibility of this choice was demonstrated through a dedicated preliminary study: an independent expert operator analyzed 150 ultrasound images acquired previously from volunteers, documenting that the distal point could be identified adequately in only about half of the images, whereas the centroid was always detected on the same images. Therefore, once the operator had placed the pubic symphysis within the onscreen ellipsoidal guide, in all of our cases the automatic algorithm was able to detect the visible portion of the target anatomical structure and to calculate its centroid. The ellipsoidal guide helped to simplify and standardize the image acquisition protocol, giving reassuring feedback to the operator and providing the automatic software with a defined and limited image area for the pubic symphysis search. Inaccuracies in determination of the actual centroid position were negligible, with a lower discordance between manually estimated and actual position for the centroid (average distance between single marked points and corresponding average point, 0.8 ± 0.4 mm) than for the distal edge (1.4 ± 0.9 mm) of the pubic symphysis. Furthermore, the automatic algorithm, employing the analytical definition of centroid, is expected to be more accurate than manual identification, reducing possible errors in centroid determination to a negligible level.

The choice of pubic symphysis reference point simply led to an offset in AoP calculation with respect to previous reports[14], this offset being a function of the centroid–distal point distance, of the head–symphysis distance and of $\sin(AoP_{distal})$, where AoP_{distal} represents the AoP measured with respect to the distal point of the symphysis. A visual comparison between the two different AoP measurements is presented in Figure 9.

Barbera *et al.*[14] developed a geometric model from which it was possible to associate the measured AoP value with a specific fetal head station, according to the classification of the American College of Obstetricians and Gynecologists (ACOG). For the range of AoP_{distal} values corresponding to the whole range of ACOG fetal head stations, the offset between AoP and AoP_{distal} can be estimated through the following formula: $AoP_{offset} = \alpha \times \sin(AoP_{distal})$, where α, which accounts for the head–symphysis distance and the centroid–distal point distance, may be approximated to a constant of 17°. Table 1 reports the association between specific fetal head stations and the corresponding AoP intervals derived from the model reported by Barbera *et al.*[14] and adapted to our AoP calculation, adopted in this work.

In this way, the data obtained through our algorithm may be used not only for monitoring the progress of labor, but also for prediction of the fetal head station and of the most probable delivery mode. Evaluation of AoP_{distal} during the second stage of labor is a widely reported method to predict the mode of delivery. Ciaciura-Jarno *et al.*[26] analyzed AoP_{distal} by performing transperineal ultrasound scans on 68 parturients and found a good correlation between greater AoP_{distal} values and the natural delivery. They found that all parturients with $AoP_{distal} > 126°$ delivered naturally, while only 15% of the patients who delivered naturally had an $AoP_{distal} < 126°$. By employing a similar approach on 23 parturients, Barbera *et al.*[25] found that when AoP_{distal} was > 120°, natural delivery followed, whereas when AoP_{distal} did not exceed 108°, Cesarean section was performed. Kalache *et al.*[15] confirmed in 26 parturients that an angle of 120° or more was associated with a 90% probability of a natural delivery. In this study, we found that all parturients whose measured AoP was > 137° delivered naturally, a result in good agreement with most of the published data, since this cut-off value corresponds to an AoP_{distal} of about 123°.

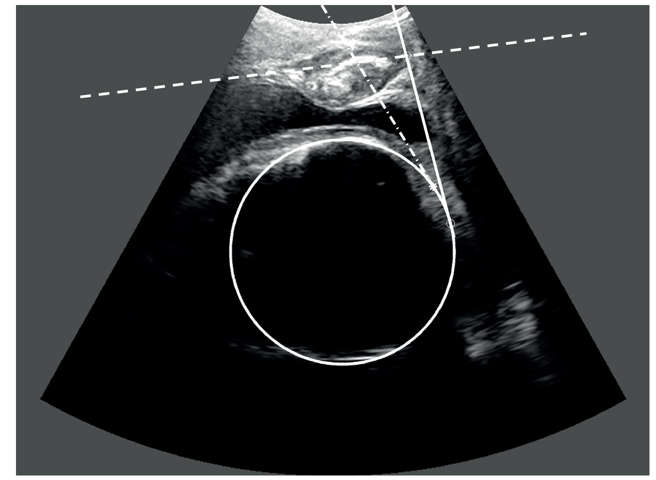

Figure 9 Visual comparison between angle-of-progression measurement according to Barbera *et al.*[14] (angle between dashed line and solid line) and to our proposed approach (angle between dashed line and dash-dot line).

Table 1 Association between each specific fetal head station according to the American College of Obstetricians and Gynecologists (ACOG) and corresponding angle-of-progression (AoP) intervals derived from geometric model reported by Barbera *et al.*[14] and adapted to AoP calculation presented here

ACOG fetal head station	*AoP (°)* Lower value	Mean	Upper value
−5	77	80	84
−4	85	87	90
−3	91	95	98
−2	99	102	105
−1	106	109	112
0	113	116	119
+1	120	122	125
+2	126	129	131
+3	132	135	137
+4	138	141	144
+5	145	147	150

In the implementation of our algorithm we made certain assumptions. We felt it was reasonable to assume that AoP did not change significantly during the 5-s sonographic acquisition. We also fitted the fetal skull with a circumference, which is not strictly correct; however, in order to calculate the AoP value, only the fetal head leading edge is considered and this is comparable to a circumference arc.

In conclusion, the translabial ultrasound approach presented in this paper is well-tolerated by patients and the automatic algorithm makes it less operator-dependent, allowing objective quantification of the AoP with a high level of accuracy. This automatic technique has the potential to reduce human error and speed up ultrasound acquisition time, which should facilitate monitoring progress of labor and ultimately decision-making regarding delivery options. Future studies will focus on extended clinical validation, also combined with the simultaneous measurement of other labor monitoring parameters through the same approach.

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Disclosure

F. Conversano, M. Di Paola and S. Casciaro are shareholders of Amolab S.r.l., a National Research Council spin-off company that may or may not benefit from the results of this study.

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SUPPORTING INFORMATION ON THE INTERNET

The following supporting information may be found in the online version of this article:

Appendix S1 Details of procedure for automatic identification of landmarks through automatic segmentation (applied only to the images of the first acquisition session)

Appendix S2 Details of procedure for automatic identification of landmarks through pattern tracking (applied only to the images of the subsequent acquisition sessions)

