Registration problems when modelling change due to surgery and growth in children with unilateral cleft lip and palate

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Introduction and Aim

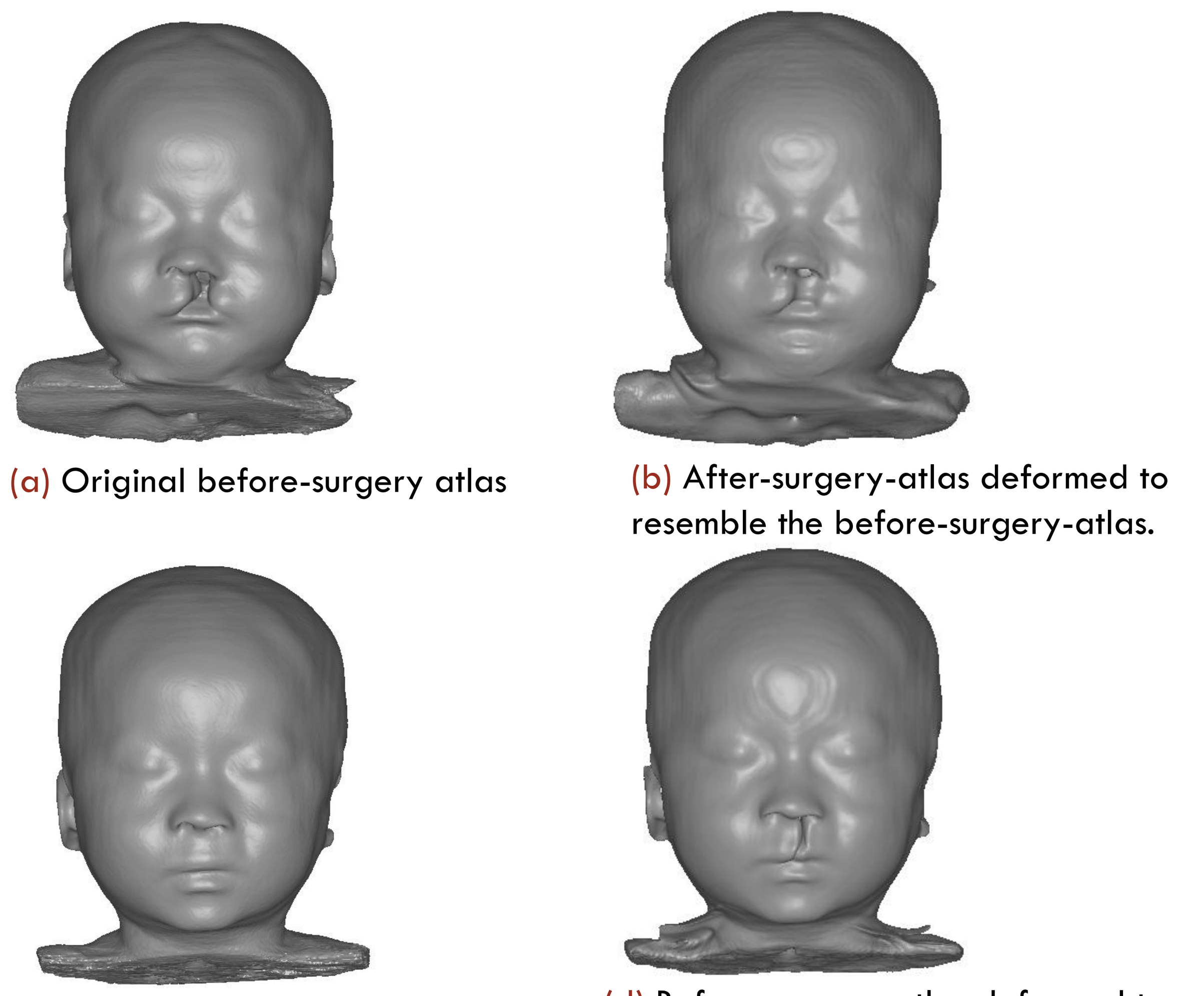
Cleft Lip and/or Palate (CLP) is the most common congenital craniofacial malformation (incidence is about 1/500 [Losee and Kirschner 2008]). CLP is caused by lack of fusion of different palatal processes in the young fetus and is typically treated by surgical rehabilitation of the lip and palate.

Non-rigid image registration based on voxel similarity measures and B-splines (henceforth called non-rigid image registration) [Rueckert et al. 1999; Schnabel et al., 2001; Studholme et al., 1999] has previously been used in order to quantify head shape and growth in individuals and groups of individuals [Ólafsdóttir et al. 2007; Thorup 2008]. The method consists of building an atlas as an average of individuals and subsequently establishing detailed point correspondence for any individual by deforming the individual to the atlas.

Non-rigid image registration fails whenever individuals to be analyzed are too morphologically dissimilar (either because of large deformations or change in topology) for the non-rigid image registration to converge to a satisfactory solution.
The aim of the study was to find a solution to the registration problems occurring when registering individuals exhibiting large morphological changes sometimes caused by surgery, as is the case in UCLP.

Material

The data material consists of 3-dimensional CT scans of 23 Taiwanese infants with unilateral cleft lip and palate (UCLP). The infants were scanned before lip repair at the age of 3 months, and again after lip repair at the age of 12 months. In UCLP, the cleft can occur on either the left or right side of the face, and in order to increase the sample size *n*, the right sided clefts were mirrored as a preprocessing step prior to analysis.



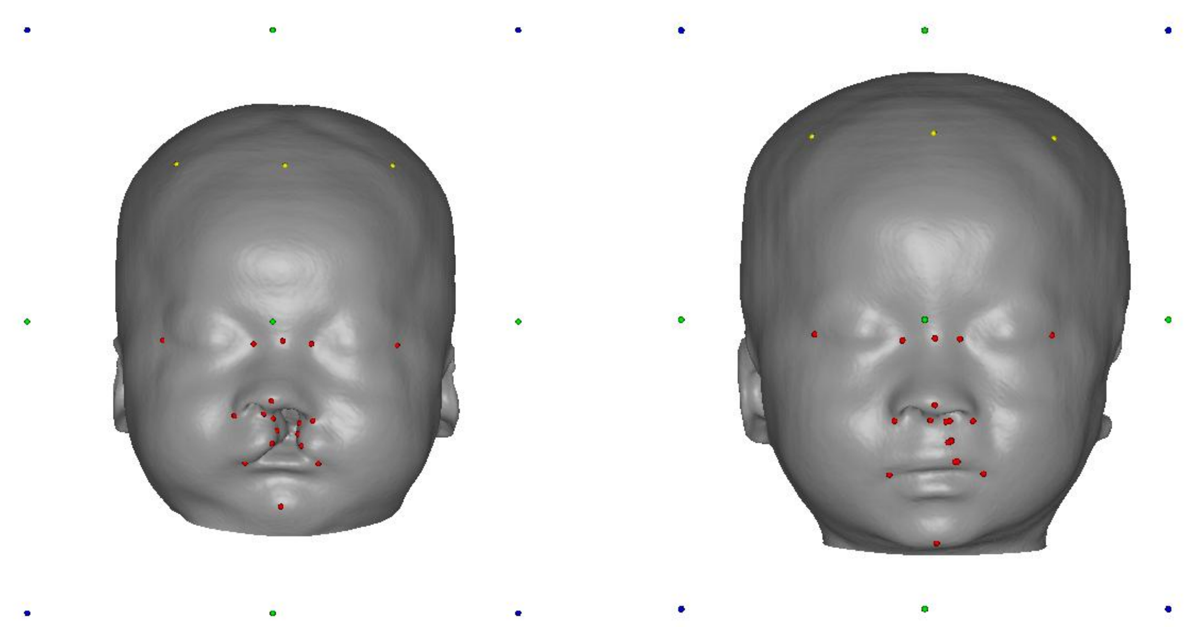
(a) Original before-surgery atlas
(b) After-surgery-atlas deformed to resemble the before-surgery-atlas.
(c) Original after-surgery atlas
(d) Before-surgery-atlas deformed to resemble the after-surgery-atlas.

Figure 1: Before- and after lip surgery atlases (n = 23) (a and c, respectively), and the problems encountered in the cleft region when registering the atlases to each other using non-rigid image registration (b and d). Similar problems occur when registering single individuals.

Method

To overcome the problems visualized in Figure 1, it is proposed to bridge the large change between the before- and after-surgery-atlases by an additional non-rigid deformation field T determined by thin-plate-splines (TPS) using manually placed landmarks (Figure 2). The method is motivated by the observation that a point distribution model containing landmarks from both ages is distinctly bi-modal, making it probable that T will be a good initial guess for the deformation field for *any* UCLP lip surgery.

Algorithm 1: Automatically determine the deformation field due to lip surgery and growth for an individual with UCLP
1) Register an individual (before surgery) to the before-surgery-atlas using non-rigid image registration. The result is a deformed individual resembling the atlas; deformation field A.
2) Deform the result from 1) to the after-surgery-atlas using landmark-based (Figure 2) TPS deformation; deformation field T.
3) Register the result from 2) to the individual after surgery using non-rigid image registration; deformation field B.
4) Compute the final deformation field F for the individual by summing the three computed deformation fields: $F = A + T + B$.
Note that the method is fully automatic, since manual landmarks need to be placed only in the atlases, "predicting" the T for an (unseen) individual.

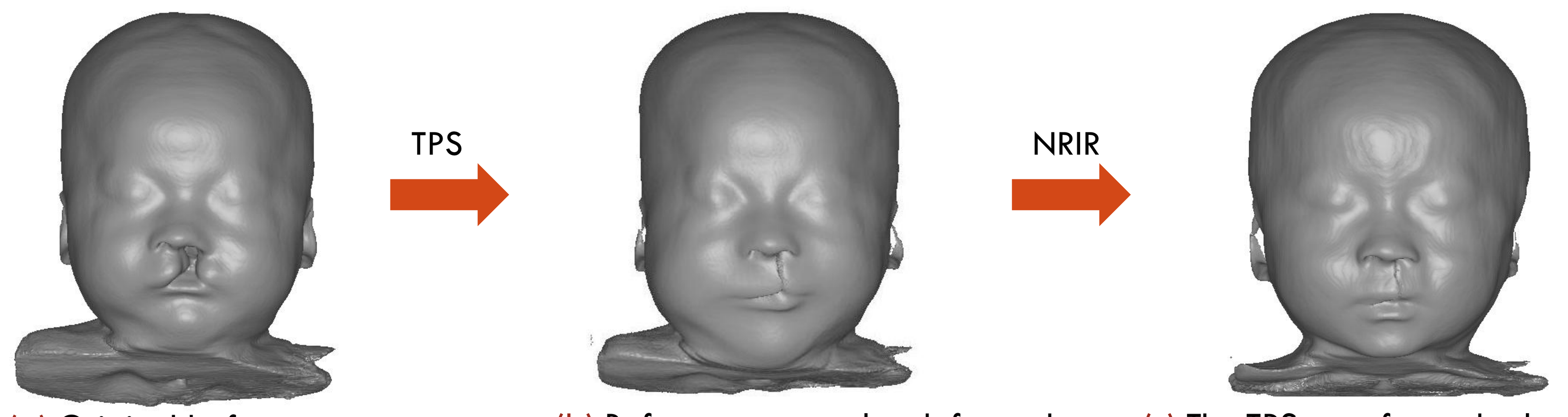


(a) Before-surgery atlas
(b) After-surgery atlas

Figure 2: Atlases with the 45 landmarks used for the TPS-transformation. There are 8 corners (blue), 6 sides (green), 9 pseudo-landmarks on skull top and neck (yellow) and 22 anatomical landmarks (red).

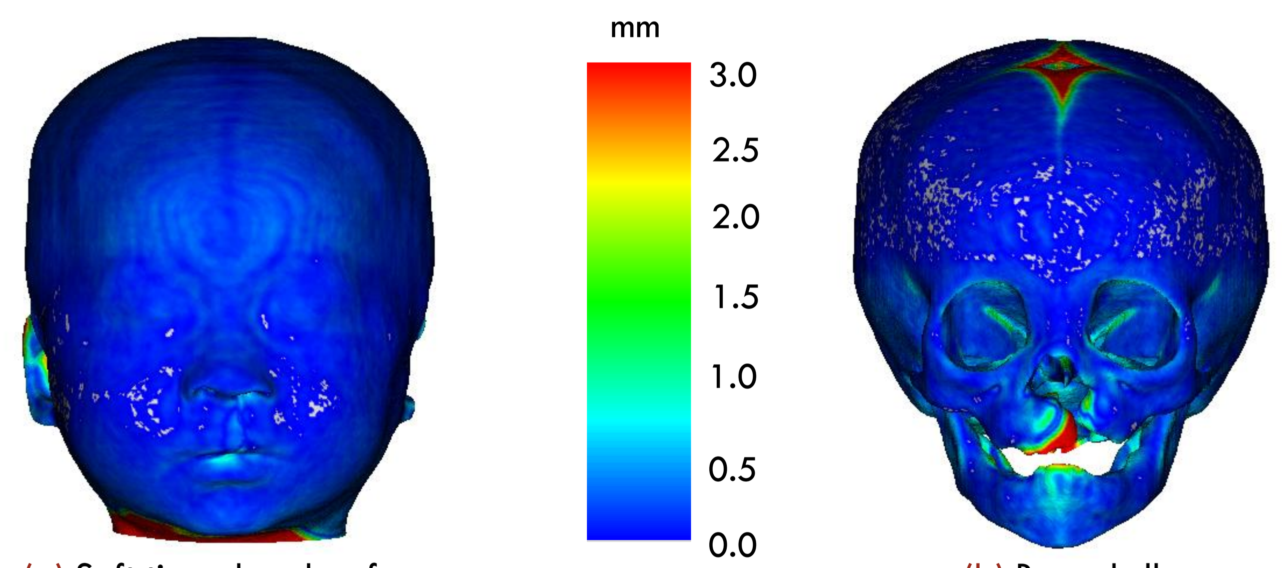
Results

A proof-of-principle was carried out by applying the deformation field T to the before-surgery-atlas (Figure 3a) and subsequently deforming the result (Figure 3c) to the after-surgery atlas (Figure 3c). A validation was carried out by computing the difference (closest distances) between the result (Figure 3b) and the after-surgery-atlas (Figure 4).



(a) Original before-surgery atlas
(b) Before-surgery-atlas deformed to resemble the after-surgery atlas using TPS.
(c) The TPS-transformed atlas deformed to resemble the after-surgery-atlas.

Figure 3: Notice how the TPS-transformation from 2) brings the cleft to an almost closure ((a) to (b)) – the head shape is, however, a bit abnormal (b). Adding non-rigid image registration (NRIR) afterwards improves the cleft closure, as well as the overall head shape, a lot visually ((a)-(c)).



(a) Soft tissue head surface
(b) Bony skull

Figure 4: Validation. Distances between the result of Algorithm 1 (applied to the before-surgery-atlas) and the "truth" (the after-surgery-atlas) (computed as closest distances between surfaces) color coded on the after-surgery-atlas.
Red color indicates regions with errors equal to or larger than 3 mm. White and blue colors indicates regions with zero or small errors. Mean errors: 0.1 mm and 0.3 mm and for soft and bone tissue , respectively.

Discussion and Conclusion

The results indicate that the use of the proposed method (Algorithm 1) will enable automatic determination of the deformation field due to lip surgery and growth in (unseen) individuals. Errors were on average small (0.1 and 0.3 mm for soft tissue facial surface and bony skull surface, respectively). The relatively large errors close to the cleft in the bony skull surface (Figure 4b) may be explained by the fact that only soft tissue landmarks were used for the TPS deformation.
A similar validation study was carried out on the deformed surfaces from Figure 1 i.e. a) was compared to b) and c) compared to d) by closest distance. Errors were on average larger than the ones found in Figure 4 (For Figure 1 (a) - (b) the errors were 1.36 and 1.19 mm and for (c) - (d) the errors were 0.23 and 0.52 mm for soft tissue facial surface and bony skull surface, respectively). This indicates that Algorithm 1 improves the registration.

Future work includes validating the method using all 23 individuals in turn as "unseen" individuals in a leave-one-out experiment. Furthermore, to include bony landmarks in the TPS registration. We also propose to build a shape model that can predict a better T for an individual than just using the average.

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Acknowledgement

For all image registrations the Image Registration Toolkit was used under licence from Ixico Ltd.

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