Masking approaches to analyse plantar pressure data of new and confident walking infants.

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Abstract

Background: Due to its easy and straightforward use, regional analysis with the "standard" mask is the most common approach for quantifying plantar pressures in infancy. Such a mask, however, identifies foot regions based on typical foot proportions and pressure gradients. Alternatively, the use of a customised mask retaining infants' feet proportions has not been explored. **Research question:** Does a customised mask scaled on infants' feet improve processing of pressure data collected during walking development compared with a standard mask? **Methods:** Thirteen infants walked across an EMED xl platform. Steps were grouped applying eight foot-regions standard and customised masks. To evaluate masks' performance, peak pressure (PP) and contact area (CA) were extracted from each region, and mask. Intra-individual coefficients of variation were then calculated for each variable, and compared between masks using a Mann-Whitney U test ($p<0.05$). Unsuccessful masks application was reported, expressed as percentage of data loss. **Results:** For CA variation, significant differences were found in all the regions but the lateral toes in new (Z= -0.184, p=0.8540) and confident walking (Z= -1.562, p=0.118). For PP variation, a significant difference was found in confident walking within the lateral midfoot (Z=-2.598, p=0.009). With the standard mask, 22-27% of data was lost in new and confident walking respectively, compared to 1.6-0% with the customised. As a result, the customised mask characterised the more variable steps, demonstrating higher variation compared to the standard mask. **Significance:** Identifying foot regions using a mask based on infants' feet proportions yielded an improved performance compared to the standard mask. With the customised mask, we retained almost all the steps and characterised the variability of the data, thereby providing an appropriate approach for infants' pressure data processing. Application of the customised mask could therefore be beneficial in future studies analysing highly variable data sets.

Keywords: plantar pressure, infancy, masking analysis, regions of interest, walking

1. Introduction

Plantar pressure data have been used to investigate typical foot function across periods of development [1]. The existing literature outlines two methods to analyse plantar pressure data in infancy, namely pedobarographic Statistical Parametric Mapping (pSPM) [2] and regional analyses with masks [3-7]. Masking analysis is the most common approach to quantification of plantar pressures in infancy and childhood [1], as this is available within software packages and data handling is straightforward. This approach also enables direct comparison of discrete values in regions of interests (ROI), and it has been commonly used by the literature in clinical populations [8-10]. Nevertheless, masking analysis results in data that is simplified into single values, depending on the number of ROI [3, 4, 7, 11], causing reduction of spatial resolution as well as plantar pressure information [12-14]. The use of pSPM in both infancy and childhood is less common, although such an approach overcomes the limitations when ROI are used [2, 15]. However, pSPM has presented computational challenges in infancy due to the variability of shape and dimensions of infants' steps and their spatial orientation in the Euclidean space [2]. This leads to complex data processing [2], leaving pSPM potentially inaccessible to researchers and clinicians without programming experience. Therefore, masking analysis is still commonly adopted [4, 5], despite its limitations.

Studies using regional analyses in infancy have reported the use of the "standard" masks, involving identification of heel, midfoot, forefoot and toe regions [3, 6, 7, 11]. Within the software used in these studies, the masks were created by implementing algorithms based on pre-defined criteria to identify ROIs (e.g., using typical foot proportions and consistent contact patterns of adults). Consequently, the manufacturer guidelines for the software used in the above works (Novel Scientific Medical, Germany) reported the definition of the heel and midfoot as 73% and 45% of the foot length from the toes to the heel respectively, whilst the forefoot and the toes were identified using pressure gradients around the peak pressures in these areas. Adopting a mask generated by algorithms based on adult foot proportions and contact patterns could limit the external validity of the data. For example, infants' feet present with different anatomical and morphological characteristics compared to adults, meaning that the standard algorithm is unlikely define ROIs correctly. Further, infants walking in self-selected directions are characterised by irregular foot shapes, dimensions and contact patterns, which can cause the presence of missing areas (e.g., toes, forefoot) [2, 16], undermining the ability of the standard algorithms to define regional boundaries.

As an alternative, many software packages also offer the possibility of customising masks for processing data, allowing researchers to define ROIs across the plantar surface. This can be based on the specific foot proportions of the sample of interest, whilst still applying the mask automatically. As a result, the customisation of the mask allows researchers to adapt it to pressure steps that are highly variable and irregular in shape, dimension and spatial orientation. This customisation still facilitates an automatic application of the mask to each step, therefore maintaining an objective approach. Nevertheless, studies have not adopted a customised mask to automatically define plantar pressures in the early stages of walking development. As a result, the following research question was posed in this work: Does a customised mask scaled on infants' feet improve processing of pressure data collected during walking development compared with a standard mask? For this purpose, we will consider: 1) the amount of variation present for each region when the two masks are applied and their differences 2) the successful masks application to the pressure steps.

2. Methods

2.1 Participants

Ethical approval was granted from the University of Brighton (LHPSCREC 17–11), and 13 infants were recruited in the Southeast of England, as part of the Great Foundation program [17]. Participants were included in the study if they were born within 37-42 weeks of pregnancy, had no signs or history of musculoskeletal and/or neurological disorders, audio, visual or sensory impairment, and were born above the 4th percentile for weight. They were excluded if they had family history or have been referred for consultation of suspected musculoskeletal or neurological condition, or if they were taking medicines (indicator of health issues) [17].

2.2 Data collection

Data was collected at the Human Movement Laboratory of the University of Brighton, where each infant was asked to attend data collection sessions on two different occasions, defined as two stages of walking:

- New walking: infants were able to take 3 to 5 steps independently;
- Confident walking: infants were able to take 10-15 steps independently and in more than one occasion, interacting with others and carrying toys while walking, navigating around objects;

Parents were asked to identify these stages and report to the lead researcher alongside videos or images of the infants performing the tasks for confirmation. Following this, parents were asked to attend the data collection session within 21 days of attaining new and confident walking. At each stage of walking, parents provided informed consent. Descriptive information of the participants are reported in Table 1.

[Table 1 here]

2.3 Testing procedure

Plantar pressure data was collected with an EMED xl platform (4 sensors per cm^2, 100 Hz; Novel, Munich, Germany). Infants walked self-directed around the laboratory space without being constrained or asked to perform specific walking tasks (e.g., walking in straight lines from one point of the testing space to another). During data collection, the walking bouts were also recorded via HD videos (Vicon Bonita 720c; Oxford, U.K). A minimum of three trials of 60-second duration were recorded for every infant and these were used to label each pressure step according to the task performed by infants (e.g., whether they were walking in straight lines, walking while turning, squatting).

2.4 Data processing

For each walking stage, all the data from independent self-directed straight walking were extracted in the standard EMED software (Novel, Munich, Germany). The steps were divided in eight ROIs, to allow for a higher-resolution approach compared to most masking approaches [7, 11, 18, 19]. Specifically, we considered both medial and lateral aspects of each region. The use of higher number of ROIs (in particular medial and lateral regions) could retain more details about plantar pressure distribution across the plantar surface in infancy (e.g., medio-lateral shifts in pressure distribution), which has been reported only once in previous research [5]. This has the potential to enhance our understanding of foot-ground interactions in infancy, generating new information about early foot function development.

The ROIs used in this work were the medial and lateral heel (MedH, LatH), midfoot (MedMF, LatMF), forefoot (MedFF, LatFF) and toes (MedT and LatT). Regions were identified following two automatic masking approaches:

- *The standard mask* was created using the Automask package (Novel, Germany), where the bisection mask command was selected to identify the medial and lateral ROIs. This mask identified the heel and the midfoot as 73% and 45% of the foot length from the toes to the heel respectively, and the forefoot and toe regions using pressure gradients around the peak pressures of these areas. Lateral and medial regions were defined within the software by a foot axis drawn from the centre of the heel to the centre of the second toe.
- *The customised mask* was created using the Automask package (Novel, Germany), where a percent mask was created, as previously reported. [5]. The proportions of each ROI were based on radiographic images of typically developing infants, using the length of the calcaneus and first metatarsals as reference measures [20, 21]. The calcaneus (defining the rear-foot) represented 31% of the foot length [20]. The forefoot and midfoot both represented 26% of the total foot length [21], whilst we estimated that the toes covered 17%. The medial and lateral portions of each ROI were divided based on 50% of foot width, defined automatically as the axis passing from 50% of the toes to the heel. As anticipated, the data was expected to be highly variable both within and between infants, [2], and therefore we decided to personalise the application of the customised mask. Accordingly, the mask was created on the pressure step that most closely matched the measured foot length at each walking stage (the step template). Then the mask was saved and applied to the entire data set of each infant at both stages of

walking. This mirrored the approach of Cousins et al [22], who manually created and applied a mask on a single foot that they identified as a within-children template.

With both approaches, steps were grouped for each participant at each walking stage and the masks were applied to the individual steps using the Group Editor package (Novel, Germany). Peak pressure (PP) and contact area (CA) were extracted for each step using the Group Mask Evaluation package (Novel, Germany). These variables were selected as they have been commonly reported in previous studies [1]. In addition, PP represents a single sensor within a ROI, while CA accounts for all the sensors that are contained within a ROI, thereby offering different aspects of masks performance.

There were instances where the mask application was unsuccessful and the lead researcher, who was experienced in plantar pressure data processing, defined this visually. The following criteria were used to define an unsuccessful mask application: 1) the mask was not applied onto the step in full, 2) only some regions were successfully identified by the mask (e.g., only the heel, or heel and midfoot, etc.) and 3) some regions were not correctly identified by the mask. In these instances, the steps were excluded from the analysis.

2.5 Statistical analysis

Pressure data for the left and right feet were randomly selected for the analysis and this approach was consistent with previous studies [3, 6, 7]. Data was managed with Microsoft Excel (Microsoft Office 2016), and analysed statistically with SPSS software (IBM Statistics, version 25). Performance of the two masks was accounted for:

- *Variation*: Intra-individual coefficients of variation (CV) were calculated across the individual steps (CV = SD/mean*100), for PP and CA, in each ROI. CVs data were checked for normality using the Shapiro-Wilk test [23]. As data were not normal, the Mann-Whitney U test was used to establish if data were significantly different between approaches ($p<0.05$). This was undertaken at each walking stage, for the ROIs and variables selected.

- *Successful mask application:* This was expressed by reporting the percent of steps where masks application was unsuccessful, considering the total number of steps originally included in the analysis, to highlight the amount of data that can be lost with the application of two approaches.

3. Results

3.1 Variation

Statistical comparison of CVs is reported within the clustered box plots for PP and CA (Figures 1 and 2). For PP, the only significant difference between approaches was in confident walking in the LatMF (Z=-2.598, p=0.009). For CA, significant differences were found in all regions except in the LatT (new walking: Z= -0.184, p=0.8540; confident walking: Z= -1.562, p=0.118).

[Figure 1 and 2 here]

3.2 Successful mask application

The successful mask application was descriptively reported as number and percentage of steps where the mask application failed according to the criteria listed above (Table 2). Example of unsuccessful mask applications are reported in Figure 3.

[Figure 3 here]

Of the 255 steps masked in new walking, the standard mask was unsuccessful for 56 steps (22% data lost), whilst unsuccessful mask application with the customised approach was recorded for four steps (1.6% data lost). In confident walking, the standard mask was unsuccessful for 143 steps out of 536 (27% data lost), whilst the customised mask applied successfully to all steps, resulted in no lost data.

[Table 2 here]

4. Discussion

This study aimed to assess the performance of a customised mask scaled on infants' feet compared to the standard mask commonly adopted within the literature [3, 6, 7], when applied to a data set of typically developing infants. This work sought to understand if the customised mask could yield an improved performance, hence constitute a more appropriate approach than the standard mask for processing infants' plantar pressure data.

One principle we used to assess masking performance was to consider the applications of both masks to the infants' plantar pressure steps, and to check how frequently these failed. In instances where the mask could not be applied, this would reflect a mask that could not adapt to the highly variable infants' steps made in self-selected directions and would lead to step exclusion and data loss. We found that the customised mask scaled to infants' feet led to a more successful application (data loss 0-1.6%) compared to the standard mask (data loss 22-27%). As anticipated above, the challenges with the standard mask application were likely due to inter-variability in shape, dimensions, and contact patterns of the infants' steps. Whilst we demonstrated that using a customised mask mitigates data loss, we also assume that personalising the customised mask application for each infant and walking stage is a crucial factor leading to a more successful result, allowing us to address the presence of within-infant variability in such a data set [2]. Being aware of the limitations related to successful mask application is important in research in this field, as it can inform the amount of data that would be necessary to obtain a sufficient sample. This means that in the case of dealing with plantar pressure data captured from infants walking in self-selected directions, researchers should be aware that the standard masking approach led to more than one in five steps being lost from analysis.

Another assessment of performance was to calculate the variation across individual steps and compare this between the two masks applied for CA and PP. In the work by Giacomozzi and Stebbins [8], the authors considered the absence of significant differences between the variation of the two masking approaches as an estimate of the appropriateness of mask performance. Whilst the LatMF was the only region demonstrating significant differences in variation for PP between masks, we found that for CA, the customised approach demonstrated significantly different results compared to the standard mask, in all regions except in the LatT. The differences of CA outputs between approaches might be explained by a combination of factors. First, the standard masks adopted in previous work [3, 6, 7] were based on algorithms that have been created using consistent foot proportions and typical contact patterns in adults. Alternatively, the customised mask of this study has been implemented to retain specific infants' feet proportions, resulting in quantification of different areas covered by the ROIs, as the two masks use different criteria to divide the plantar surface. Second, the CA was measured using all the sensors present in a specific region, whilst PP data relied on just the sensor with the highest pressure among the number in that region. Thus, it is possible to say that CA values are more sensitive to masking approaches than PP.

As anticipated, the strengths of the masking approaches would lie within the ability to define regions more consistently across participants. A consistent identification of the regions from the approaches means that the inter-individual variability of the data set would not have an influence on the mask application. Accordingly, we found that the customised mask demonstrated larger coefficients of variation in output, particularly for CA, compared to the standard mask, defining an inconsistent mask application. However, it is important to highlight that the application of the standard mask led to more unsuccessful applications to the steps, which caused the removal of more data from the analysis. By processing a smaller volume of data with the standard mask, we excluded steps that were more variable as part of the sample rather than including them. Hence, the lower coefficients of variation in PP and CA demonstrated by the standard mask do not reflect its more efficient performance and justify its use. Rather, the coefficients of variation being higher in the customised mask are positive representations of performance in this instance, as they reflect the capability of such a mask to process the data that was collected almost in full.

Whilst this study provided new information about plantar pressure data processing in infancy, we wanted to acknowledge two limitations with our work. First, the masks were applied to 13 infants and although the volume of data processed was large, we appreciate that this is a relatively small sample size. Linked with this, we recruited a sample of typically developing infants. We understand that the extrapolation of our findings to clinical populations (e.g., infants with clubfeet), therefore, might be limited. Further work to explore our approach in clinical populations is warranted.

5. Conclusion

The customised mask and its personalised application to a data set of infants at early stages of walking development allowed us to retain nearly all the plantar pressure steps collected. The differences in performance compared to the standard mask were related to the area of contact, likely due to the presence of different criteria that have been used to identify regions of the masks. The analysis of plantar pressure data in new and confident walkers could therefore benefit from a masking approach implemented using criteria based on specific proportions of infants' feet. Consequently, the customised mask proposed in this work can be considered as an appropriate alternative to the standard mask for the quantification of plantar pressure in this sample of infants. Such an approach could therefore be considered for other pressure analyses, where data sets of highly variable plantar pressure are present.

6. References

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	New walking				Confident walking			
	Min	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**
Age at data collection (months)	11.0	13.2	1.0	14.7	12.3	15.1	1.3	17.1
Age when first reported by parents (months)	10.7	12.7	0.9	14.2	11.8	14.5	1.3	16.4
Days between reaching the stage and data collection (days)	7.0	13.8	5.5	21.0	7.0	15.7	15.7	21.0
Mass (kg)	9.2	10.8	1.1	12.5	9.6	11.3	1.2	13.4
Height (cm)	71.5	75.5	2.8	81.1	71.9	77.8	3.6	83.3
Foot length (cm)	9.7	11.4	0.8	12.6	10.6	12.0	0.8	13.1
Foot width (cm)	4.4	5.4	0.4	5.9	4.3	5.4	0.5	6.2

Table 1. Descriptive information for participants at each of the stages of walking.

	Standard mask			Customised mask		
Stages of walking	**Steps initially included**	**Steps not masked**	**% of data loss**	**Steps initially included**	**Steps not masked**	**% of data loss**
New walking	255	56	22	255	4	1.6
Confident walking	536	143	27	536	0	0

Table 2. Report of total amount of steps data originally considered in the analysis (column 1), total amount of pressure data failed to be masked (column 2) and percent of data loss with respect to the amount of data initially included in the analysis (column 3), for the standard and costumised masks, respectively.

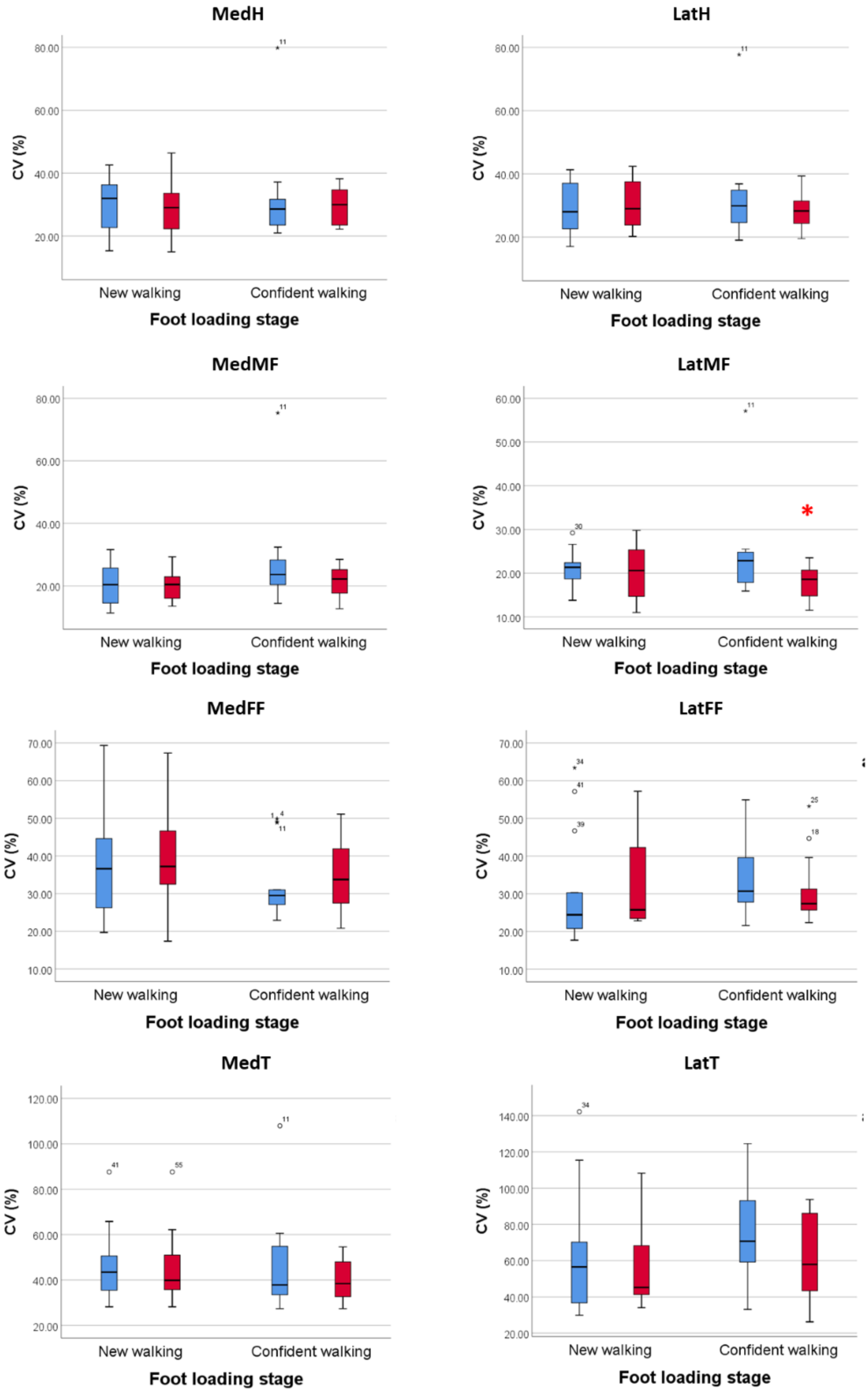

Figure 1. Box plot of inter-individual coefficients of variation in peak pressure. Blue and red boxes represent the variance of the standard and the customised masks, respectively. The red star indicates where the output of the customised mask significantly differs from the standard mask.

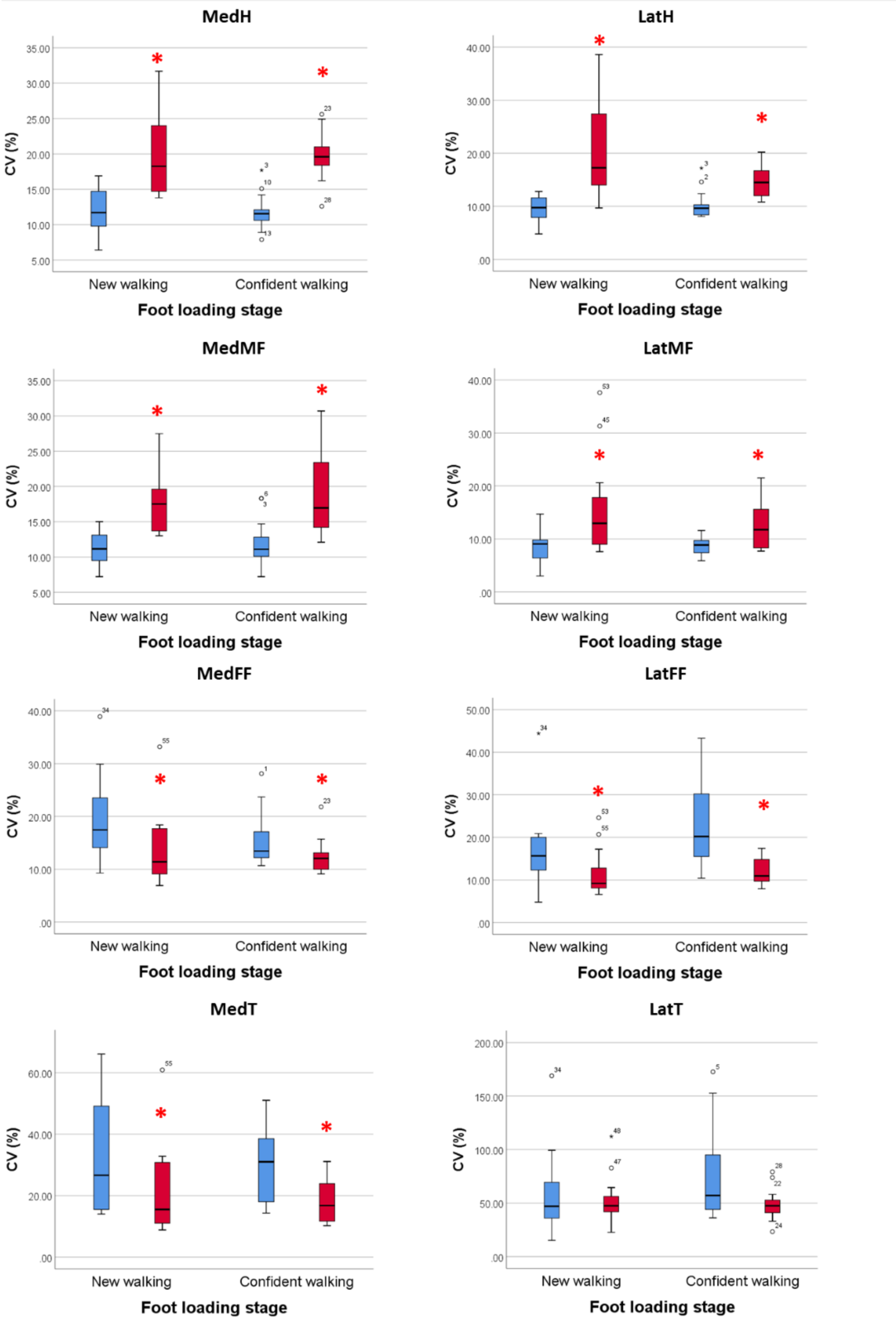

Figure 2. Box plot of inter-individual coefficients of variation in contact area. Blue and red boxes represent the variance of the standard and the customised masks, respectively. The red star indicates where the output of the customised mask significantly differs from the standard mask.

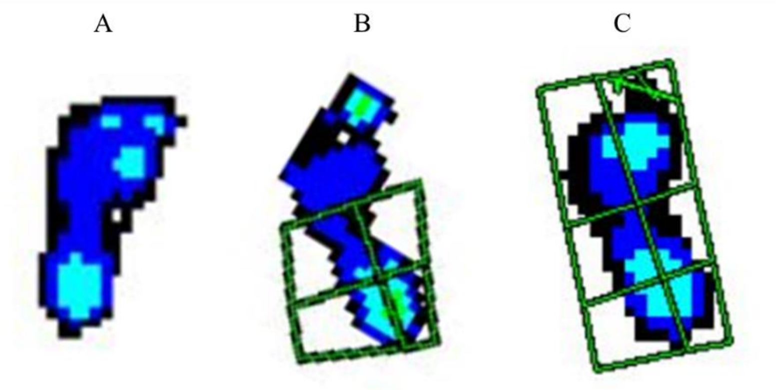

Figure 3. Example of unsuccessful mask application (these are reported based on the application of the standard mask, but we adopted the same criteria to detect an unsuccessful custom mask application): A) Mask that was not applied onto a step in full, B) Mask that only partially applied to the step, C) Mask that failed to identify correctly a region (in this case, the hallux). The lead researcher visually identified if these error in the mask application occurred.