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# Determination of optimal shoe fitting for children tennis players: Effects of inner-shoe volume and upper stiffness

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## A b s t r a c t

The purpose of this study was to determine the optimal inner-shoe volume for children tennis players. Sixteen participants, aged from 8 to 12 years old assessed comfort of 6 shoes, which were a combination of 3 lasts (thin, medium and wide) and 2 upper constructions (flexible and stiff), while a sock equipped with textile sensors was measuring the pressure applied on their foot. The thin last was based on the proportion of an adult last. The widest shoes produced the lowest pressure on the 1st and 5th metatarsal heads, the medial midfoot and the medial and lateral heel ( $p < 0.05$ ), whilst they were perceived the most comfortable for the 3rd and 5th metatarsal heads, the 5th metatarsal base and the medial and lateral heel ( $p < 0.05$ ). These outcomes indicated that footwear manufacturers should design wider shoes for children than for adults.

## Keywords:

Footwear

Comfort

Pressure measurement

## 1. Introduction

Tennis is a popular sports with tens of millions of players participating worldwide and wearing appropriate tennis shoes is a critical necessity for player's performance and practice in safety (Pluim et al., 2007). Fit and comfort were reported to be the most important shoes properties expected by adult tennis players (Sterzing et al., 2014). However, even though designing comfortable sports shoes is a primary concern for footwear manufacturers, Llana et al. (2002) highlighted that only 68% of adult tennis players considered their footwear as comfortable. Providing a suitable shoe fit and comfort is difficult due to the wide range of individual's feet morphologies and fit preferences (Kouchi et al., 2005; Mauch et al., 2009). Furthermore, tennis is characterized by multidirectional displacements and sudden brakings that require support and resistance of the shoes (Llana-Belloch et al., 2013). This translates technically into a pressure to avoid movements of the foot within the shoe and reinforcements to ensure a long lasting durability,

which can create discomfort points.

Designing proper shoes for children is an even greater challenge since it was observed that more than 50% of them were poorly shod (Byrne and Curran, 1998; Walther et al., 2008). The first reason is likely that children's shoes are generally scaled-down from adults' one whereas their foot morphologies are different (Dowling and Steele, 2001). It was notably shown that the ratio between the foot width and the foot length decreased over the course of time during growth (Müller et al., 2012). Another possible reason is that although the shoes can be suitable when purchasing, they may become too small very quickly due to the rapid foot growth. From 10 to 14 years old, the child's foot grows in average from 12 to 15 mm in length and from 3 to 4 mm in breadth per year, which represents approximately 2 sizes (Kouchi, 1998). Parents may thus replace shoes too late because they are not aware that they are no longer suitable for their child.

Despite these difficulties, wearing suitable shoes may be even more important for children tennis players since their foot structure is not yet completely consolidated and is constantly growing (Mauch et al., 2009). During growth, child's foot morphology is more sensitive to external factors than adults due to the constant remodelling process of bones (Rossi and Tennant, 1984). It was

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shown that habitual use of footwear influenced the overall shape of the foot and thus that wearing inappropriate shoes may contribute to foot deformities (D'Août et al., 2009; Staheli, 1991). For instance, wearing shoes of insufficient length during childhood was shown to increase the hallux angle, thus increasing the risk of hallux valgus disorders later (Klein et al., 2009). Even though a proper length is a primary concern, the forefoot, midfoot and rearfoot breadth and circumference are important as well to ensure the natural foot development. The exertion of strong compression may inhibit normal development of the foot and damage tissues (Echarri and Forriol, 2003; Xiong, 2008). In addition, an improperly fit of the shoe may lead to injuries due to a lack or excessive movements of the foot within it (Staheli, 1991; Wolf et al., 2008).

Perception questionnaires were used to quantify shoe fit and comfort in adults (Au and Goonetilleke, 2007; Mills et al., 2010; Mündermann et al., 2002). However, questionnaires only provide a subjective measurement and the reliability of children's answers remains questionable. Individuals' subjective perception of footwear fit was correlated with objective measurements, such as dimensional differences between foot and shoe last (Au et al., 2011; Witana et al., 2004). This method was notably used to define optimal inner-shoe dimensions for adult tennis players and to highlight fit perception differences between regular and occasional players (Herbaut et al., 2016a). Although this method was shown to provide relevant information, a limitation is that footwear comfort is not only given by the shoe last but also by upper compounds properties since they can play a role on the pressure applied on the foot as a function of their elasticity. For instance, soccer players perceived a better fitting of shoes upper made in kangaroo leather compared with those made in synthetic leather (Olaso Melis et al., 2016).

Therefore, some studies examined the relationship between pressure on foot dorsal side and comfort perceived by subjects (Cheng and Hong, 2010; Hagen et al., 2010; Jordan and Bartlett, 1995). While some researchers found no significant correlation (Hagen et al., 2010), other succeed in founding a relationship between them and concluded that pressure may be a valuable objective measure to assess fit and comfort of the shoe (Hennig, 2012). Jordan et al. (1997) reported lower pressures on the foot dorsal side for the most comfortable shoes. Cheng and Hong (2010) also found negative correlations between the pressure and comfort perceived on several dorsal foot locations. Conversely, in another study, the reduction of foot dorsal pressures was related to the decrease of upper comfort (Jordan and Bartlett, 1995). These contradictory outcomes might indicate the existence of a trade-off between the minimal pressure required for safety in sports activities, as it is the case in tennis where a lot of intense multidirectional displacements are required, and a too high pressure that may generate discomfort (Llana et al., 1998).

As it was previously mentioned, optimal inner-shoe dimensions for male tennis players were defined (Herbaut et al., 2016a). However, besides the fact that the proportions of the child's foot are different from those of adults (Müller et al., 2012), the relationship between pressure on the foot and comfort perceived by children tennis players remains unknown. It was shown that females had lower pressure pain thresholds than males on several foot locations (Xiong et al., 2012). Thus, it is quite possible that children perceive pressure and discomfort differently from adults as well. Therefore, the main objective of this study was to determine the optimal inner-shoe volume for children tennis players and to compare it to the one previously defined for adults (Herbaut et al., 2016a). Children's tennis displacements are generally less intense than adults' ones. We thus hypothesized that adult tennis players are ready to bear more pressure on the foot to the detriment of comfort in order to benefit from a better support. Conversely, children would prefer

looser shoes to practice tennis since shoe support would be less essential for them. The secondary objective was to examine the influence of both the shoe last and the upper construction on the pressure applied on the child's foot. The hypothesis was that the shoe last plays a more important role than the elasticity of the upper construction on the pressure exerted on the foot.

## 2. Methods

### 2.1. Participants

Sixteen parents gave informed written consent for the participation of their 16 children in the study that complied with the Declaration of Helsinki and that was approved by the local ethics committee. All participants were boys from 8 to 12 years old, wearing Eu-36, injury-free and playing tennis at least once a week (Table 1). The international tennis level of the players was between ITN 6 and 8. They were able to control where the ball is going, to sustain a short rally and to cover the court with multiple tennis-specific movements.

### 2.2. Shoe conditions

Six pairs of tennis shoes (size Eu-36) were made with 3 different lasts: Thin (T), Medium (M) and Wide (W), and 2 different compounds: Flexible (F) and Stiff (S). The flexible upper was based on an existing tennis shoe model (®Artengo TS900 JR 2012) and was composed of soft polyester textile and synthetic leather. A layer of polyurethane was added on the stiff upper to rigidify the overall structure (Fig. 1).

The length of all the shoes was set at 10 mm more than the mean foot of the participants, as defined as the proper fit for children (Klein et al., 2009). Since it has been previously determined that the thin last was the optimal one for tennis practice in adults (Herbaut et al., 2016a), the thin last was thus adapted by homothetic transformation from the optimal adult last to the mean child foot proportions. The medium last was exactly identical except that the metatarsal girth was 7 mm larger. The wide last was 4 mm wider for metatarsal width, 14 mm larger for metatarsal girth and 4 mm wider for heel width. These differences were confirmed by the inner-shoe measurements (Table 2).

The upper stiffnesses were measured by a traction test (ISO 13934-1) with a dynamometer (Amsler HC5,®Zwack Roell, Ulm, Germany). The upper of each shoe prototype was cut into two parts along the longitudinal direction, which were clamped between the jaws of the test machine. A constant rate of jaws separation was set at  $100 \pm 10$  mm/min until a displacement of 10 mm. The upper stiffness was computed as the ratio between the maximal traction force applied by the dynamometer and the maximal displacement of the jaws. The flexible uppers were in average 21% less rigid than the stiff uppers ( $71.1 \pm 4.9$  N/mm vs.  $85.7 \pm 3.3$  N/mm).

**Table 1**  
Characteristics of the participants.

	Mean	SD	Min	Max
Number of hours of play per week	3.8	± 1.7	2.0	7.0
Age (years old)	9.7	± 1.5	8.0	12.0
Height (m)	1.39	± 0.03	1.33	1.45
Body mass (kg)	33.6	± 4.2	28.0	42.0
Foot length (mm)	227.1	± 7.3	214.0	238.0
Metatarsal width (mm)	85.7	± 6.5	74.0	99.0
Metatarsal girth (mm)	226.8	± 10.8	199.0	244.0



Fig. 1. Lateral view of the prototypes with flexible upper (up) and stiff upper (down).

**Table 2**  
Main inner-dimensions (in mm) of the shoes assessed by the participants.

Last	Thin		Medium		Wide	
	Flexible	Stiff	Flexible	Stiff	Flexible	Stiff
Shoe	TF	TS	MF	MS	WF	WS
Length (SL)	237.2	235.6	235.9	236.6	236.2	236.1
Metatarsal width (SMW)	79.6	79.0	80.1	79.9	84.3	83.1
Metatarsal girth (SMG)	214.1	213.8	220.3	222.9	228.3	227.5

### 2.3. Experimental apparatus

#### 2.3.1. Foot and inner-shoe dimensions measurements

Foot measurements were performed with a digital calliper and a measuring-tape on the right foot of each participant in standing position. Two measurements were done by the experimenter and if a difference was observed between them, a third measurement was performed. The recorded dimensions were foot length (FL), foot metatarsal width (FMW) and foot metatarsal girth (FMG) (Fig. 2). Inner-shoe dimensions were obtained with a SID three-dimensional (3D) scanner (UCS<sup>®</sup> D.O.O., Vrhnika, Slovenia). After a calibration of the scanner, each shoe was filled with small metal ball bearings and a 3D point cloud of the inner surface of the shoe was reproduced out of several x-ray images of the filled shoe (Omrcen and Kopac, 2010). Inner-shoe dimensions extracted were shoe length (SL), shoe metatarsal width (SMW) and shoe metatarsal girth (SMG) (Fig. 2). The technical errors of measurement were analysed through a pilot study and were found to be 1 mm for FL, FMW, SL and SMW and 1.5 mm for FMG and SMG (Herbaut et al., 2016a).

#### 2.3.2. Pressure distribution

Recently, an innovative device consisting in a sock equipped with textile pressure sensors (Taxisense, Montceau-les-mines, France) was designed and validated to measure the pressure

applied on the foot and to assess footwear comfort (Herbaut et al., 2016b). The sampling frequency was set at 30 Hz and the root-mean-square error was lower than 5%. In the present study, the sock was equipped with 8 textile pressure sensors with a surface of 2.25 cm<sup>2</sup> (1.5 × 1.5 cm) on the following locations: 1) external side of 1st metatarsal head (MT1), 2) navicular (NAV), 3) medial heel (MHL), 4) top of 3rd metatarsal head (MT3), 5) top of instep (INS), 6) lateral heel (LHL), 7) tuberosity of 5th metatarsal and 8) external side of 5th metatarsal head (MT5) (Fig. 3).

#### 2.3.3. Questionnaire

A questionnaire was designed based on Mündermann's recommendations (Mündermann et al., 2002). Fifteen centimetres visual analogue scales (VAS) were used and it contained 1 question on overall comfort and 1 question for each foot location where a sensor was positioned: "How do you like the comfort of the shoe on this location?". A pilot study highlighted that some children presented difficulties to rate the shoes on the VAS. Therefore, to facilitate the understanding of the questionnaire, it was adapted using 5 smileys equally distributed under the 15-cm VAS (instead of words at left and right extremities). Smileys were defined as "very uncomfortable" (0 cm, red), "quite uncomfortable" (3.75 cm, orange), "neither uncomfortable nor comfortable" (7.5 cm, yellow), "quite comfortable" (11.25 cm, light green) and "very comfortable" (15 cm, dark green) (Fig. 4).

### 2.4. Procedure

All the tests were performed in a local tennis club on a Greenset court. Participants were asked to remove their shoes then foot dimensions were measured in half body weight bearing state with a digital calliper and a tape-measure. It was shown to be a more representative measurement of a shoe fitting situation compared with a sitting position since foot metatarsal width and girth increase in mean from 2.5 mm and 3.7 mm under adult weight-bearing, respectively (Xiong et al., 2009). The sock with textile pressure sensors was put on right foot of each participant and each sensor was correctly repositioned on each anatomic point of interest. A first 5 s recording was launched to have the offset of measurement.

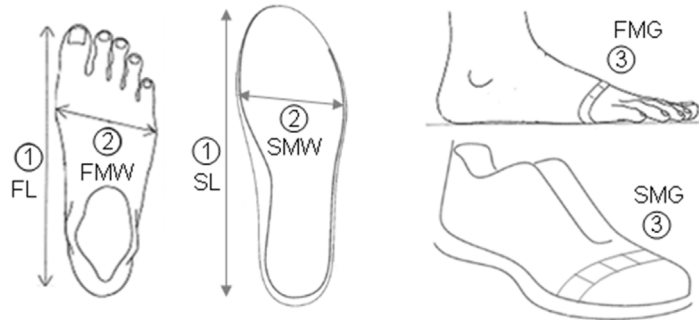
Each pair of shoes was worn randomly and children were asked to fasten them at their personal preference. They were then asked to stand up, to position the feet from hip width gap and do not move the foot within the shoe during the 5 s recording to measure the pressure applied by shoe upper on the foot. Immediately after the pressure measurement, they filled in the comfort questionnaire for each shoe condition with the help of the experimenter to indicate the foot location for each question to avoid any mistake. The instructions given to the participants were to stay in standing position and to focus only on the sensations of the right foot.

### 2.5. Statistical analysis

The mean and standard deviation were calculated for pressure and comfort rating variables. Statistical analyses were performed using Statistica version 9.0 (Statsoft, Inc, Tulsa, OK, USA) and the significance threshold was set at the 0.05 level of confidence.

Firstly, a 3 × 2 (3 lasts × 2 upper constructions) repeated measures analysis of variance (ANOVA) was applied with shoe as the repeated factors, and pressure and comfort rating as dependent variables. When a significant effect was found, a *LSD Fisher* post-hoc was performed.

Secondly, correlation between mean pressure and average comfort rating were assessed on each foot location. The mean pressure on 1st and 5th metatarsals was associated to "forefoot



	Foot	Shoe
<b>Length (1)</b>	<b>FL:</b> distance from the calcaneus to the tip of the longest toe	<b>SL:</b> distance between the outmost outer points in length
<b>Metatarsal Width (2)</b>	<b>FMW:</b> distance measured with digital calliper between the 1st and the 5th metatarsal heads	<b>SMW:</b> distance between the outmost outer points in breadth
<b>Metatarsal Girth (3)</b>	<b>FMG:</b> circumference of the foot measured with tape and passing by the 1st and the 5th metatarsal heads	<b>SMG:</b> circumference of shoe at 69% of SL and inclined for passing by the outmost outer points in breadth

Fig. 2. Definitions of foot and inner-shoe dimensions.

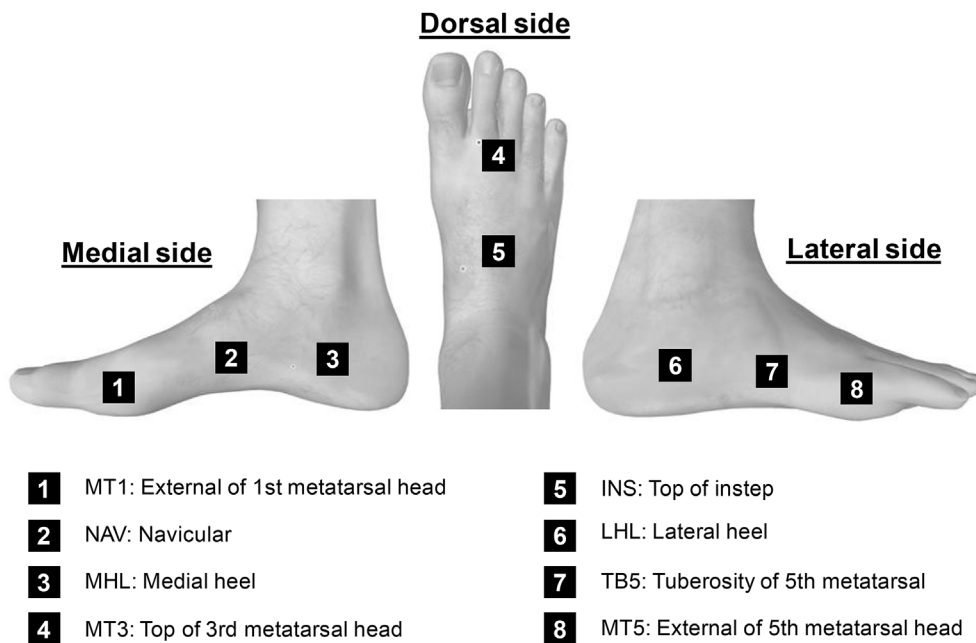


Fig. 3. Locations of the textile pressure sensors on the foot.

width” pressure, medial and lateral midfoot to “midfoot width” pressure, medial and lateral rearfoot as “rearfoot width” pressure because in the same shoe condition, pressure can decrease on the medial part and increase on the lateral part, or inversely as a function of the way to position the foot in the shoe but global pressure can remains similar.

### 3. Results

#### 3.1. Pressure and comfort rating of shoes

##### 3.1.1. Effect of upper construction on pressure and comfort rating

No main effect of upper construction or interaction on pressure

was revealed for each location. A main effect of upper construction was found on comfort rating for the 3rd metatarsal head (MT3) ( $p < 0.05$ ). Shoes with a flexible upper were felt more comfortable than shoes with a stiff upper (mean flexible upper = 12.5, mean stiff upper = 10.7).

##### 3.1.2. Effect of last on pressure and comfort rating

A significant main effect of last was found on pressure for the 1st metatarsal head (MT1), navicular (NAV), medial heel (MHL), 5th metatarsal head (MT5) and lateral heel (LHL) ( $p < 0.05$ ). LSD Fisher Post-hoc revealed that the wide last produced less pressure than thin and medium lasts for each location (Fig. 5).

A significant main effect of last was found on comfort rating for

NAME: \_\_\_\_\_ SHOE: \_\_\_\_\_

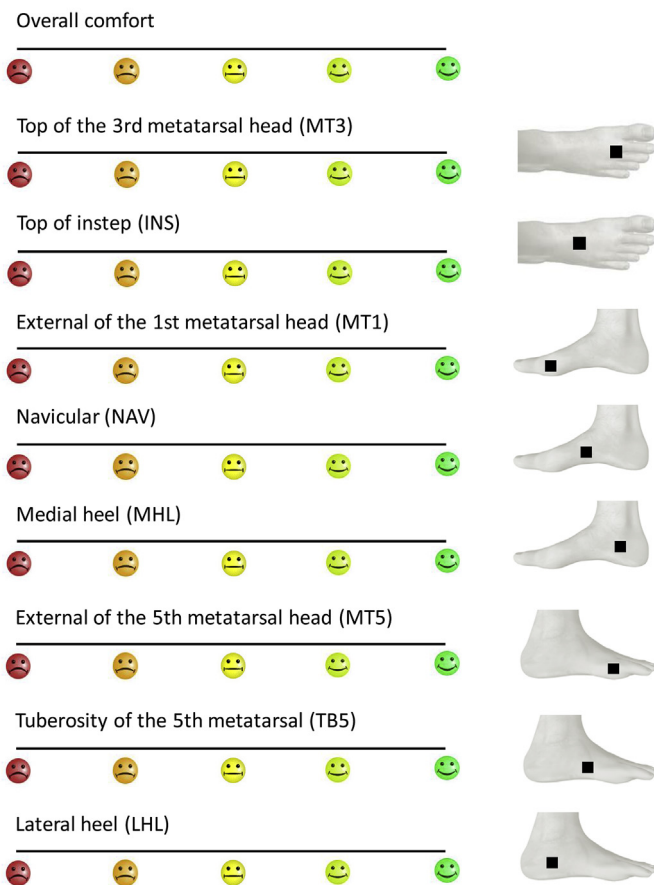


Fig. 4. Questionnaire filled in by the participants for each shoe condition.

the 3rd metatarsal head (MT3), medial heel (MHL), 5th metatarsal head (MT5), tuberosity of the 5th metatarsal (TB5) and lateral heel (LHL) ( $p < 0.05$ ). LSD Fisher Post-hoc revealed that the mean comfort rating in shoes made with the wide last was better than in shoes made with thin and medium lasts (Fig. 6).

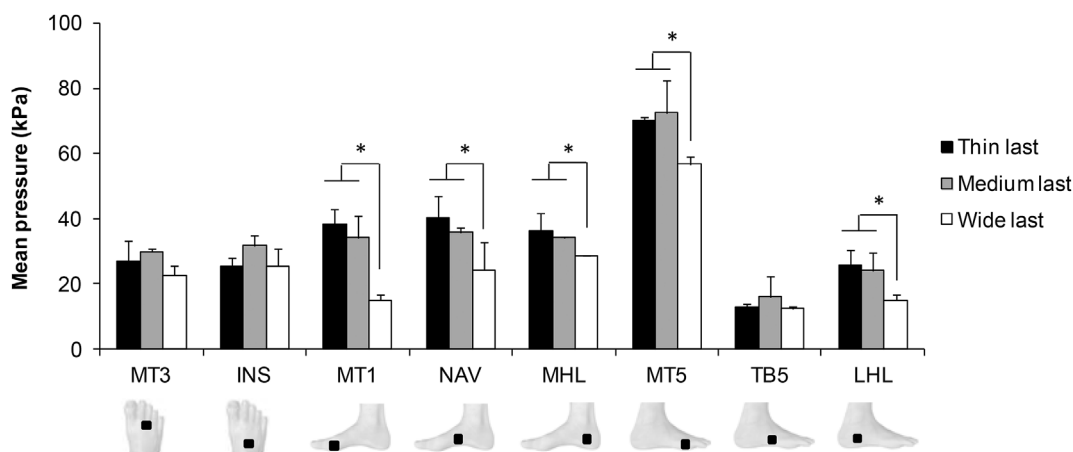


Fig. 5. Mean pressure for each foot location as a function of the last (black: mean of thin last-flexible upper (TF) and thin last-stiff upper (TS), grey: mean of medium last-flexible upper (MF) and medium last-stiff upper (MS), and white: mean of wide last-flexible upper (WF) and wide last-stiff upper (WS)).

### 3.2. Correlations between pressure and comfort rating

Compiling all pressure and comfort rating data measured for the 6 shoes, significant correlations were found between pressure and comfort rating for the 1st metatarsal head (MT1), the 5th metatarsal head (MT5) and the medial heel (MHL) ( $p < 0.05$ ). Significant correlations between mean pressure and mean comfort ratings of the forefoot width (1st and 5th metatarsals), the midfoot width (medial and lateral midfoot) and the rearfoot width (medial and lateral heel) were found (Fig. 7).

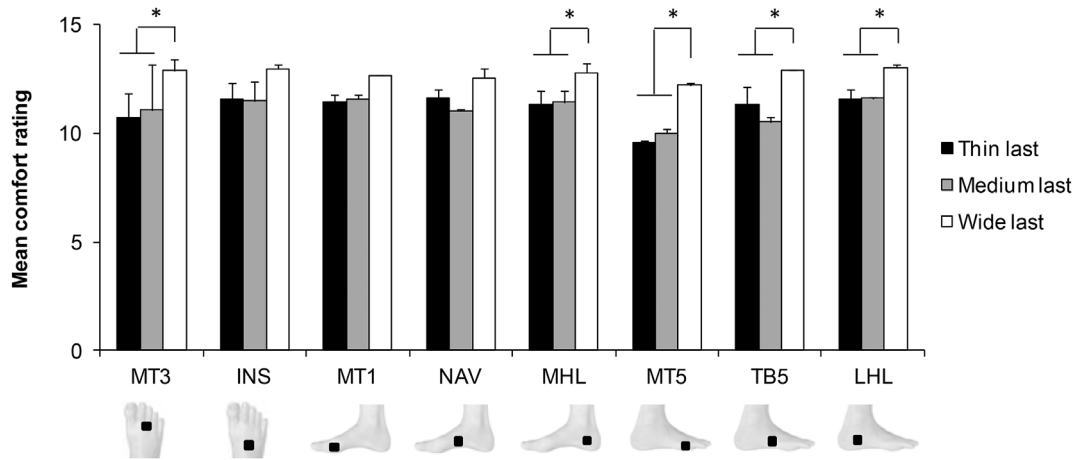
## 4. Discussion

### 4.1. Effects of upper construction on pressure and comfort

The upper construction neither influenced inner-shoe volume nor pressure applied on the 8 foot locations. Regarding comfort ratings, no effect of upper construction was detected except on the top of the 3rd metatarsal head, where flexible upper was perceived more comfortable than stiff upper ( $12.5 \pm 0.9$  vs  $10.7 \pm 1.6$ ,  $p < 0.01$ ). However, the pressure on this location was not significantly higher in stiff shoes compared to flexible shoes ( $27.1 \pm 5.6$  kPa vs.  $25.9 \pm 4.1$  kPa,  $p > 0.05$ ). The flexible upper may allow the toes to move upward more and the participants may have felt this sensation comfortable, even though they were asked to keep the foot immobile during pressure acquisition. Since the pressure sensor was located on the 3rd metatarsal head, it was not possible to detect it. The absence of effect of the upper construction on comfort perception for the 1st and the 5th metatarsal heads was in contrast with Olasso-Melis et al. study (2016), showing that kangaroo leather was preferred to synthetic leather which is less flexible. The difference in terms of elasticity was not measured in this study and was maybe larger than the 21% difference between the flexible and the stiff upper construction in the present study. However, using much more flexible materials for shoe upper would be at the expense of support and might place children at risk of performance degradation and injuries, especially during lateral movements in tennis (Llana-Belloch et al., 2013). Furthermore, Olasso-Melis et al. (2016) allowed the participants to walk with the shoes, which maybe helped them to better feel the differences between shoes upper materials.

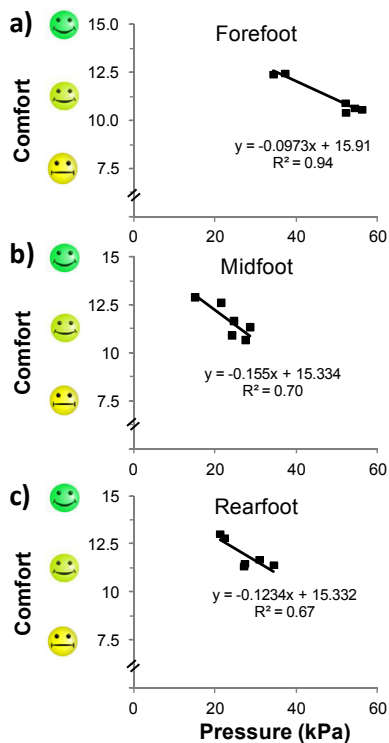
### 4.2. Effects of last dimensions on pressure and comfort

Shoes made with the medium last (MF and MS) had a bigger



**Fig. 6.** Mean comfort rating (from 0 to 15) for each foot location as a function of the last (black: mean of thin last-flexible upper (TF) and thin last-stiff upper (TS), grey: mean of medium last-flexible upper (MF) and medium last-stiff upper (MS), and white: mean of wide last-flexible upper (WF) and wide last-stiff upper (WS)).

#### 4.3. Pressure and comfort rating



**Fig. 7.** Pearson correlations between mean pressure and mean comfort rating of a) the forefoot, b) the midfoot and c) the rearfoot.

SMG than shoes made with the thin last (TF and TS) but the mean pressure applied on metatarsals and the mean comfort rating were similar between shoes made with them. Shoes made with the wide last (WF and WS), which was wider at SMW, produced less pressure and were felt more comfortable than other shoes on forefoot, midfoot and rearfoot widths. It showed that a difference in SMW as little as 3 mm had a significant effect on pressure and comfort rating on metatarsals. It was not surprising since a difference of 3 mm in width corresponds to more than one size, which was shown to be perceptible in adults (Herbaut et al., 2016a).

Mean pressures on all foot locations were ranged from 10 to 40 kPa, except for the 5th metatarsal head where it reached almost 70 kPa. The mean pressure was higher on the 5th metatarsal head than on the 1st metatarsal head, which was consistent with Cheng & Hong's study (2010). That may be explained by the more protruding shape of 5th metatarsal head compared to the 1st metatarsal head and/or by the rigid reinforcement present on the lateral part of the tennis shoes.

All the shoes were in average perceived rather comfortable for all locations and no shoe condition obtained an average rating under 9 on the comfort scale from 0 to 15. It may be due to the fact that shoes selected for this study were based on existing commercially shoes that children are used to wear. It would signify that all the pressures applied on the foot by the tested shoes were acceptable for the majority of children tennis players. However, shoes made with the wide last were perceived significantly more comfortable than those made with thin and medium lasts, globally and for 5 out of the 8 foot locations. Therefore, according to comfort preferences of the participants in a static wearing, using the wide last to make tennis shoes for children seems to be the best solution compared to the two other lasts and should provide a good comfort given the relatively high ratings of comfort reported by the participants. Nevertheless, further tests in dynamic situations would be necessary to verify if the widest shoe is the most suitable for children tennis players in real game conditions.

#### 4.4. Correlation between pressure and comfort rating

Except for the medial heel, the 1st and the 5th metatarsal heads, correlations between pressure and comfort ratings were not significant ( $p > 0.05$ ). It was shown that some individuals had a low sensitivity and that each had its own sensory threshold to pressure (Mündermann et al., 2002). However, correlations between mean pressure and mean comfort rating on forefoot width (mean of 1st and 5th metatarsals), midfoot width (mean of medial and lateral midfoot) and rearfoot width (mean of medial and lateral heel) were significant. It may indicate that, except for metatarsal heads that were the most sensitive areas, participants had some difficulties to dissociate medial and lateral feelings in terms of comfort (Dohi et al., 2002). However, it seems that most of the participants were able to perceive the global pressure on forefoot, midfoot and rearfoot width, and to assess footwear comfort reliably.

#### 4.5. Practical recommendations

The participants preferred the widest shoe compared to the medium shoe and the thin shoe, whereas the latter was scaled-down from the adult optimal tennis shoe determined in a previous study (Herbaut et al., 2016a). The preferred SMW was 2 mm less than foot and the preferred SMG was 1 mm more than foot for children tennis players, while the optimal SMW and SMG were 8 mm and 15 mm less than foot for adult tennis players, respectively. These results confirmed the initial hypothesis that children prefer larger shoes compared to adults, and were in accordance with the recommendations of D'Août et al. (2009) and Walther et al. (2008), who advocated sufficiently roomy shoes, especially in the forefoot region, to ensure proper foot development. It could be explained by the fact that adults project themselves in usage and know that they need support for their practice while children would not be able to do so. Furthermore, adults are generally more used to wear tight shoes due to their experience and may be able to tolerate more pressure than children. In addition, a limitation of this study was that it is not known how a wider shoe would be perceived by children tennis players. It would deserve to be evaluated to determine with certainty the optimal inner-shoe volume for tennis practice.

The second outcome was that using a more flexible upper construction did not allow to significantly reduce the pressure applied on the foot and to improve shoe comfort. Therefore, using a wider shoe last for children compared with an adult shoe last seems to be a best way than providing a more flexible upper to design proper shoes for children. On the other hand, using a 21% stiffer compound to reinforce the upper structure did not decrease the perceived comfort by the participants. Therefore, it can be a good solution to improve the durability of the tennis shoe without degrading comfort.

#### 5. Conclusion

This study showed that scaling-down adult tennis shoes for children tennis players, without taking into account their specificities, did not offer the optimal comfort. Children participating in this study preferred the widest shoes, which were 4 mm wider for metatarsal width and 14 mm larger for metatarsal girth and which produced less pressure on most of the foot locations compared to the shoes scaled-down from adult ones. The results showed that inner-volume had a predominant importance on comfort compared to the stiffness of the upper construction. A future investigation is needed to verify whether the preferred shoes in this study according to the static assessment are the preferred shoes in usage as well.

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