Brazilian Journal of Physical Therapy 2020;xxx(xx):xxx—xxx

abrapg·ft Associação Brasileira de Pesquisa e Pós-Graduação em Fisioterapia

Brazilian Journal of Physical Therapy

https://www.journals.elsevier.com/brazilian-journal-of-physical-therapy

ORIGINAL RESEARCH

What is the foot strike pattern distribution in children and adolescents during running? A cross-sectional study

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Received 21 March 2020; received in revised form 22 June 2020; accepted 2 October 2020

KEYWORDS
Barefoot;
Kids;
Runners;
Shod

Abstract
Background: There is a lack of studies describing foot strike patterns in children and adolescents. This raises the question on what the natural foot strike pattern with less extrinsic influence should be and whether or not it is valid to make assumptions on adults based on the knowledge from children.
Objectives: To investigate the distribution of foot strike patterns in children and adolescents during running, and the association of participants' characteristics with the foot strike patterns.
Methods: This is a cross-sectional study. Videos were acquired with a high-speed camera and running speed was measured with a stopwatch. Bayesian analyses were performed to allow foot strike pattern inferences from the sample to the population distribution and a supervised machine learning procedure was implemented to develop an algorithm based on logistic mixed models aimed at classifying the participants in rearfoot, midfoot, or forefoot strike patterns.
Results: We have included 415 children and adolescents. The distribution of foot strike patterns was predominantly rearfoot for shod and barefoot assessments. Running condition (barefoot versus shod), speed, and footwear (with versus without heel elevation) seemed to influence the foot strike pattern. Those running shod were more likely to present rearfoot pattern compared to barefoot. The classification accuracy of the final algorithm ranged from 80% to 88%.

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https://doi.org/10.1016/j.bjpt.2020.10.001

Please cite this article in press as: Giacomini BA, et al. What is the foot strike pattern distribution in children and adolescents during running? A cross-sectional study. *Braz J Phys Ther.* 2020, https://doi.org/10.1016/j.bjpt.2020.10.001

Conclusions: The rearfoot pattern was predominant in our sample. Future well-designed prospective studies are needed to understand the influence of foot strike patterns on the incidence and prevalence of running-related injuries in children and adolescents during running, and in adult runners.

Introduction

Running is very popular worldwide and is considered a beneficial activity for general well-being and good health.[1–3] A survey in England revealed that 12% of the population are runners.[4] In the United States, it is estimated that around 60 million people run on a regular basis.[5] Recently, researchers have been debating whether running gait parameters could influence performance[6,7] and/or the risk of running-related injuries (RRI).[8,9] The foot strike pattern is a biomechanical concept related to the part of the foot that first touches the ground when running.[10] The foot-strike patterns for runners have been described as rearfoot (initial contact with the ground occurs at the heel), midfoot (posterior and anterior portions of the foot simultaneously contact the ground), and forefoot (anterior region of the foot comes into contact with the ground first).[11]

Running injuries have multifactorial aetiology and are associated with history of previous injuries and training factors.[12] However, it is unknown whether these injuries can be related to biomechanical factors, such as the foot-strike pattern. Previous studies evaluated the distribution of foot strike patterns among adult runners and found that the rearfoot is the most common foot strike pattern, although there is some variation reported for the type of runner (elite or amateur).[6,10,13] In fact, there is no recommended foot strike pattern to improve performance and/or to prevent RRIs, and therefore runners seem to be influenced by the media, shoes industry, or the environment.

Childhood is an extremely important phase for motor development, but there is a paucity of evidence describing the foot strike patterns in children and adolescents populations. This raises the question on what the natural foot strike pattern with less extrinsic influence should be, and if foot strike patterns change over time. It is important to understand whether or not it is valid to make assumptions on adults based on the knowledge from children research.[14] One of the main references used today that seeks to understand the influence of growth and development on the running patterns adopted by children and adolescents is a book chapter from the 1960s.[15] The few previous studies conducted in children and adolescents report that the foot strike pattern is likely to be influenced by the footwear with the rearfoot pattern being the most common.[16,17] Therefore, this study aimed to investigate the distribution of foot strike patterns in children and adolescents during running, and the association of participants' characteristics with the foot strike patterns identified using an algorithm developed by a supervised machine learning procedure.

Methods

Study design

This was a cross-sectional study conducted with children and adolescents from private and public schools in the state of Sao Paulo, Brazil. The private setting was composed of five units of a private school located in the city of Sao Paulo with approximately 2000 students from nursery I (3 years-old) to 9th grade (14–15 years-old). The public setting was composed of three units of municipal schools located in the city of Cubatão with approximately 2000 students also from nursery I to 9th grade. An authorisation signed by the director of the private school and by the Cubatão city hall was collected *a priori*, allowing the study to be conducted within the institutions and using the respective sports complexes. The 12-meter track where the students performed the running assessments was established in a space on the premises of the schools. During all data collection the physical education teacher of the school was present.

Participants

After the distribution of approximately 4000 invitations to the students of both schools, we had 415 children participating in the study. All parents or legal representatives of the participants signed the assent form, in which they stated that they had been informed about the objectives of the study and the techniques and procedures performed, and agreed to the voluntary participation of the children for whom they are responsible. This research project was approved by the Research Ethics Committee of Universidade Cidade de São Paulo. The children and adolescents in the study were used to habitual physical activities as part of the school curriculum.

Data collection

The study participants were given a questionnaire, which they brought to their parents or legal guardians and delivered to the researchers before participating in the study. In the questionnaire, parents or legal guardians completed information about body mass and height and they also had multiple choice questions related to the child's sports practice. Before or after each test, the participant's leg length was measured and also some missing data from the questionnaire were collected if necessary (e.g., if the parents did not fill in the questionnaire with their child's body mass

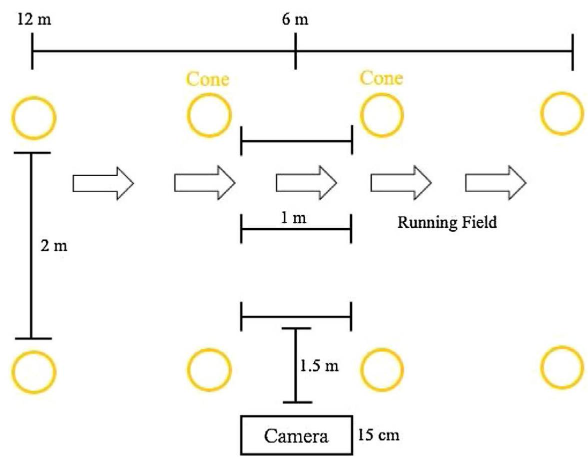

Figure 1 Map of the experimental area.

and height, these variables were measured by the assessor). The running assessment route was 12-meter long using the school's own space where the students were familiarised to sports practice. The camera was positioned on the right side of the lane. Data collection was acquired in a single session. There was no standardisation of running speed, only advice to perform the test in the way they understood as the most comfortable. The speed of the participants was also captured through stopwatch along the 12-meters.

A high-speed camera was used to evaluation the foot strike pattern during running. The camera was positioned on a tripod, 15 cm from the ground and at a distance of approximately 150 cm from the side of the path through which the participants ran (Fig. 1). The camera had an image acquisition frequency of 300 Hz. We anticipated that children and adolescents may have some variability in their foot strike pattern,[18,19] so each participant performed three running assessments for each condition (shod and barefoot), for a total of six recordings for each participant. The order of the running assessment condition was randomly determined. The randomisation procedure was performed in blocks according to the classes and using coin tossing.

Video analysis

Images of the foot strike patterns of all participants were captured and analysed using a video analysis program (Kinovea v.0.7.10). The six running assessments of each participant were evaluated by two independent examiners. The foot strike pattern was defined according to which foot area initially touched the ground and classified as follows[16]: (1) rearfoot, when the participant touched the ground first with the posterior third of the foot, (i.e., heel region); (2) midfoot, when the when the posterior and anterior portions of the foot simultaneously contact the ground; and (3) forefoot when the front of the foot initially touches the ground. We also evaluated running pace (steps/minutes), stride length (cm), running speed (m/s), and type of footwear (classified as: with or without elevation in the heel region or others).

Data analysis

Descriptive analyses were performed to summarise the sample data. Continuous variables presenting an approximate normal distribution were summarised using means and the standard deviations (SD). Numeric variables presenting non-parametric distributions were summarised using medians and 25%–75% interquartile range (IQR). Dichotomous and categorical variables were summarised using frequency distribution (n) and percentages. Distributions were assessed by inspecting histograms and probability density functions. The participants were categorised according to phases of motor development[20]: (1) 3–5 years old; (2) 6–7; (3) 8–10; (4) 11–13; and (5) 14 or older.

Bayesian analyses were performed to allow inferences for the descriptive proportion of foot strike patterns from the sample to the population distribution. Dummy variables were created representing the binomial distributions for each foot strike: rearfoot, midfoot, and forefoot. The posterior distribution of foot strike patterns was obtained from a compromise of a proper weak informative prior (beta distribution with the following hyperparameters: $\alpha = 2$; $\beta = 2$) and the data likelihood (i.e., binomial distribution). Posterior distributions were summarised using the posterior median and the 2.5%–97.5% interval; that is, the 95% equal tail credible interval (CrI).

A supervised machine learning procedure was implemented to develop an algorithm aimed at classifying participants as rearfoot, midfoot, or forefoot strike patterns. First, the database was randomly divided into three datasets: (1) a training dataset containing 80% of the participants; (2) a validation dataset containing 20% of the participants; and (3) a testing dataset containing 20% of the participants. Because the database contained repeated measurements, the randomisation scheme was programmed to allocate the entire participant's data block in only one of the three datasets to yield three independent datasets. An initial algorithm containing all variables of interest (i.e., age, sex, body mass index, running condition, running speed, type of footwear, participation in sports, and school) was developed and 'trained' in the training dataset. Afterward, the developed algorithm was investigated with regard to validation to check the accuracy of the model. Then, the parameters of the model were revised and 'trained' again in the training dataset to optimise its accuracy performance.[21–23] Thereafter, the optimised algorithm was implemented in the validation dataset again to update its accuracy performance. Lastly, the final accuracy of the model was investigated in the testing dataset.

All algorithms were based on logistic mixed models[24] including a dichotomous variable indicating rearfoot, midfoot, or forefoot strike patterns as the dependent variable. A participant indicator variable was included as random effects in all models to account for repeated measurements. Model optimisation was achieved by variable selection using Bayesian Information Criterion (BIC). The results of the models were presented as odds ratios (OR) and 95% frequentist confidence intervals (CI). All analyses were performed in R version 3.5.0 (R Foundation for Statistical Computing, Vienna, Austria).

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Results

The participants' characteristics by age groups representing the phases of motor development are described in Table 1. A total of 415 children and adolescents were included in this study, representing about 10.4% of the source population (n = 415 from approximately 4000 children and adolescents). From a total of 2490 running assessments conducted (1245 shod and 1245 barefoot), 19 (0.8%) were disregarded because it was not possible to determine the foot strike pattern in the video analysis. On average, 57% (95%CrI: 52, 61) of the valid assessments were classified as rearfoot, 25% (95%CrI: 21, 29) were classified as midfoot, and 19% (95%CrI: 16, 23) were classified as forefoot strike pattern. Of the shod runners' assessments, 71% (95%CrI: 65, 77) were rearfoot, 17% (95%CrI: 12, 22) were midfoot, and 13% (95%CrI: 9, 18) were forefoot strike pattern. Of the barefoot runners' assessments, 42 % (95%CrI: 35, 49) were rearfoot, 33% (95%CrI: 27, 39) were midfoot, and 26% (95%CrI: 21, 32) were forefoot strike pattern.

Accuracy and sensitivity of the final algorithm

Table 2 presents the results of the full models performed in the first training, and the optimised models performed in the second training of the classification algorithm. The classification accuracy of the algorithm composed of the full models in the validation dataset was 62% (95%CI: 57, 67). The classification accuracy of the algorithm composed of the optimised models in the validation dataset was 82% (95%CI: 78, 86). The classification accuracy of the algorithm composed of the optimised models in the testing dataset was 75% (95%CI: 70, 79). The accuracy of the final algorithm in classifying each foot strike pattern is described in Table 3. Sensitivity was higher for rearfoot while specificity was higher for forefoot strike pattern. Negative predictive values were similar among foot strike patterns and were higher than positive predictive values except for forefoot strike pattern. The accuracy for forefoot strike pattern was higher than those for rearfoot or midfoot strike patterns.

Discussion

Main findings

The distribution of foot strike patterns in children and adolescents during running yielded a rearfoot predominance. The distribution was significantly higher toward the rearfoot strike pattern when children and adolescents wore shoes compared to the barefoot condition. According to the logistic mixed models, the running condition (barefoot versus shod), running speed, and type of footwear (with versus

Table 1 Characteristics of children and adolescents in this study (n = 415).

Characteristics	Age groups (years)				
	3–5	6–7	8–10	11–13	14–15
Age groups	82 (19.8)	86 (20.7)	106 (25.5)	110 (26.5)	31 (7.5)
Weight (kg)	19.5 ± 3.7	23.8 ± 4.6	33.4 ± 7.8	45.2 ± 9.1	52.3 ± 8.6
Height (cm)	107.3 ± 6.8	118.4 ± 8.8	135.0 ± 10.5	154.6 ± 9.2	160.8 ± 9.6
BMI (kg/m^2)	17.0 ± 2.7	17.0 ± 4.5	18.6 ± 4.5	18.8 ± 2.8	20.1 ± 2.1
Participation in sports					
Yes	26 (31.7)	50 (58.1)	68 (64.2)	66 (60.0)	17 (54.8)
No	56 (68.3)	36 (41.9)	38 (35.8)	44 (40.0)	14 (45.2)
Type of footwear					
With heel elevation	64 (78.0)	48 (55.8)	60 (56.6)	37 (33.6)	4 (12.9)
Without heel elevation	17 (20.7)	38 (44.2)	44 (41.5)	66 (60.0)	25 (80.6)
Others	1 (1.2)	0 (0.0)	2 (1.9)	7 (6.4)	2 (6.5)
Right leg (cm)	51.7 ± 7.5	59.9 ± 5.6	69.1 ± 5.3	84.3 ± 6.1	88.1 ± 5.6
Left leg (cm)	51.9 ± 7.5	60.0 ± 5.7	69.2 ± 5.4	84.2 ± 6.1	88.0 ± 5.6
Length of stride (cm)[a]					
Barefoot	80.6 ± 9.4	88.3 ± 9.2	99.5 ± 11.3	105.3 ± 16.2	101.6 ± 13.1
Shod	86.9 ± 8.8	94.0 ± 11.8	131.2 ± 291.0	108.5 ± 16.6	111.7 ± 15.9
Speed (m/s)[a]					
Barefoot	3.5 ± 0.4	3.0 ± 0.6	2.6 ± 0.5	3.2 ± 0.4	3.2 ± 0.3
Shod	3.7 ± 0.5	3.2 ± 0.6	2.8 ± 0.5	3.3 ± 0.5	3.2 ± 0.3
Foot strike pattern[b]					
Rearfoot	62.5 (51.9, 72.3)	55.1 (44.7, 65.2)	45.8 (36.7, 55.2)	62.0 (52.9, 70.6)	59.0 (42.1, 74.5)
Midfoot	28.1 (19.2, 38.2)	26.8 (18.3, 36.6)	29.2 (21.2, 38.2)	19.3 (12.7, 27.2)	19.4 (8.7, 34.5)
Forefoot	11.5 (5.9, 19.4)	20.0 (12.6, 29.1)	25.5 (18.0, 34.3)	20.0 (13.4, 28.0)	28.2 (15.1, 44.4)

Data are number (%), mean ± standard deviation, or median (95 % Bayesian equal tail credible interval).
BMI: body mass index.
[a] Data summarised using linear mixed models to account for repeated measurements.
[b] The foot strike pattern probability distributions were estimated using Bayesian analyses to allow foot strike pattern inferences from the sample to the population distribution.

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Table 2 Results of the logistic mixed models.

Variables	Full models			Optimised models (variable selection based on BIC)		
	Rearfoot OR (95%CI)	Midfoot OR (95%CI)	Forefoot OR (95%CI)	Rearfoot OR (95%CI)	Midfoot OR (95%CI)	Forefoot OR (95%CI)
Intercept	*0.02 (0.00, 0.91)*	*0.95 (0.09, 10.62)*	*0.51 (0.01, 27.63)*	*0.01 (0.00, 0.27)*	*2.96 (0.45, 19.43)*	*0.15 (0.00, 4.91)*
Age groups						
3–5 years	*Reference*	*Reference*	*Reference*	–	–	–
6–7 years	2.48 (0.62, 9.85)	0.71 (0.31, 1.64)	0.62 (0.13, 2.96)	–	–	–
8–10 years	1.02 (0.23, 4.55)	0.59 (0.23, 1.49)	2.73 (0.54, 13.72)	–	–	–
11–13 years	3.48 (0.82, 14.75)	0.37 (0.15, 0.90)*	1.16 (0.25, 5.41)	–	–	–
14–15 years	13.11 (1.52, 113.11)*	0.13 (0.03, 0.53)*	0.90 (0.10, 8.23)	–	–	–
Sex						
Male	*Reference*	*Reference*	*Reference*	–	–	–
Female	5.60 (2.13, 14.71)*	0.51 (0.29, 0.91)*	0.33 (0.12, 0.91)*	–	–	–
BMI (kg/m^2)	0.96 (0.82, 1.14)	1.06 (0.96, 1.18)	1.00 (0.84, 1.19)	1.07 (0.94, 1.22)	0.97 (0.90, 1.05)	0.98 (0.85, 1.14)
Condition						
Barefoot	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*
Shod	15.38 (9.58, 24.68)*	0.29 (0.20, 0.40)*	0.20 (0.12, 0.32)*	22.35 (13.15, 38.01)*	0.27 (0.19, 0.39)*	0.15 (0.09, 0.25)*
Speed (m/s)	2.40 (1.48, 3.90)*	0.62 (0.43, 0.90)*	0.55 (0.33, 0.91)*	2.48 (1.49, 4.11)*	0.64 (0.44, 0.93)*	0.50 (0.28, 0.88)*
Type of footwear						
With heel elevation	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*
Without heel elevation	0.34 (0.12, 0.95)*	0.94 (0.50, 1.79)	4.04 (1.33, 12.24)*	0.27 (0.09, 0.81)*	0.68 (0.36, 1.29)	13.69 (4.03, 46.46)*
Participation in sports						
No	*Reference*	*Reference*	*Reference*	–	–	–
Yes	0.64 (0.20, 2.09)	1.89 (0.90, 3.98)	1.00 (0.29, 3.45)	–	–	–
School						
Private (São Paulo)	*Reference*	*Reference*	*Reference*	–	–	–
Municipal (Cubatão)	1.82 (0.59, 5.58)	1.13 (0.56, 2.28)	0.41 (0.13, 1.36)	–	–	–

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Table 3 Accuracy of the final algorithm in classifying running foot strike patterns in children and adolescents.

Outcomes	Foot strike patterns		
	Rearfoot Estimate (95%CI)	Midfoot Estimate (95%CI)	Forefoot Estimate (95%CI)
Sensitivity	93.2% (89.2, 95.7)	55.3% (45.7, 64.6)	49.5% (39.4, 59.5)
Specificity	64.4% (57.5, 70.8)	88.9% (85.0, 91.9)	99.1% (97.4, 99.7)
Positive predictive value	76.0% (70.7, 80.5)	61.3% (51.1, 70.6)	93.8% (83.2, 97.9)
Negative predictive value	88.7% (82.4, 92.9)	86.3% (82.2, 89.5)	87.9% (84.2, 90.8)
Positive likelihood ratio	2.62 (2.16, 3.18)	5.00 (3.51, 7.11)	55.55 (17.67, 174.65)
Negative likelihood ratio	0.11 (0.07, 0.17)	0.50 (0.40, 0.62)	0.51 (0.42, 0.63)
Accuracy	80.1% (76.1, 83.6)	80.8% (76.8, 84.3)	88.6% (85.2, 91.2)

95%CI: 95% confidence interval.

without heel elevation) seemed to influence the foot strike pattern. Children and adolescents running shod were significantly more likely to present a rearfoot strike pattern compared to those running barefoot (71% versus 42%, respectively). Children and adolescents running faster were also more likely to use a rearfoot strike pattern compared to those with lower running speed. Finally, children and adolescents using footwear with heel elevation were more likely to use a rearfoot strike pattern compared to those without heel elevation. The accuracy of the foot strike pattern classification algorithm yielded a moderate-to-good probability of correct classification of children and adolescents in the respective foot strike patterns; that is, using the algorithm developed and presented in this study one might correctly classify children and adolescents in rearfoot, midfoot, or forefoot strike patterns about 75% of the time during running.

Foot strike pattern distribution and associated factors

Our findings corroborate previous studies. A study[16] investigated the effects of footwear on foot strike patterns comparing children and adolescents who were habitually barefoot with those habitually shod walkers. The authors found higher prevalence of rearfoot pattern during shod condition (86% shod versus 63% barefoot). Other studies[17,25] investigated the foot strike pattern during running in children and adolescents and also the influence of barefoot and shod conditions on foot strike patterns. The authors found a higher proportion of rearfoot in the shod condition compared to barefoot (85% shod versus 60% barefoot).[25] Similar to adults, the foot strike pattern of children and adolescents may be influenced by footwear. One possible explanation for these findings is that in footwear conditions there is the shoes' cushion, which allows rearfoot contact and facilitating the rearfoot pattern.[19] One previous study[16] also reported slightly higher speed for the rearfoot condition. Although these results are similar to our results, we believe that the motor development pattern in children play the main role on the influence of the forefoot pattern instead of the running speed.[20]

We found that heel elevation influenced foot strike pattern in children and adolescents during running, in which those using footwear with heel elevation were more likely to present a rearfoot strike pattern. One study[18] investigated whether the foot strike pattern was modified at the moment that adolescents take the shoes off. The authors analysed treadmill running in three conditions: barefoot; footwear with heel elevation; and footwear without heel elevation. The rearfoot strike pattern was more frequently observed in those running with heel elevation compared to those with the other two conditions.[18] Interestingly, another study[26] showed that young children presented a lower proportion of rearfoot strike pattern compared to adolescents while running. However, in our study we did not find an association of age category with foot strike patterns.

Strengths and limitations

We have used a machine learning procedure implemented in the data analysis to develop, train, optimise, internally validate, and test an algorithm to classify foot strike patterns in children and adolescents during running, with the purpose of improving the generalisability and the external validity of our results. This study has some limitations. First, the cross-sectional design does not allow us to draw any cause-effect relationship. Second, the non-standardisation of footwear during data collection might be a confounding factor in the classification of foot strike pattern. Yet, allowing the participants to use their own/preferred footwear during the running assessments might increase the external validity of our study. Third, running speed was collected through stopwatch along the 12-meters track, which could have introduced error in recording speed compared to a photoelectric cell system.

Implications for practice and future directions

This study added scientific evidence on the distribution of foot strike patterns in children and adolescents in a wide age range and, subsequently, in a wide range of motor development phases. Our findings can help with the development of future prevention and treatment strategies for children and adolescents. Prospective studies investigating the motor development from childhood to adolescence, adolescence to adulthood, and adulthood to old age are paramount to a broader understanding of motor development during the lifespan. Certainly, these tasks and research processes are

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challenging and will probably require wide collaborations with multicentre studies, or even the utilisation and merging of big data from governmental and/or non-governmental organisations. Despite the challenge, we believe that a call for such an action is required. Also, future well-designed prospective studies are needed to understand the influence of foot strike patterns on the incidence and prevalence of RRIs in children and adolescents during running, and in adult runners.

Conclusions

A rearfoot strike pattern was predominant among children and adolescents during running. The distribution was significantly higher toward the rearfoot strike pattern when children and adolescents wore shoes compared to the barefoot condition. The running condition (barefoot versus shod), running speed, and type of footwear (with versus without heel elevation) seemed to influence the foot strike pattern. The developed machine learning algorithm presented good accuracy and have correctly classified children and adolescents in rearfoot, midfoot, and forefoot strike patterns.

Conflict of interest

The authors declare no conflicts of interest.

Contributors

ADL and BAG were involved in the conceptualisation and in designing the study. BAG was responsible for the data collection. BAG and LH cleaned the data. LH was responsible for conducting the data analyses. TPY, ADL and LH interpreted the data. All authors were involved in the drafting and revision of the manuscript for intellectual content and all approved the final version of the article. All authors had full access to the data (including statistical reports and tables) and can take responsibility for the integrity of the data and the accuracy of the data analysis.

Funding

This study had no funding sources.

Ethical approval

This study was approved by the Research Ethics Committee of the Universidade Cidade de São Paulo (UNICID), CAAE: 16710413.9.0000.0064.

Informed consent

Informed consent was obtained from all individual participants included in this study.

Transparency

The authors affirm that the manuscript is an honest, accurate, and transparent account of the study being reported. No important aspects of the study have been omitted. Any discrepancies from the study as planned have been explained.

Data availability statement

Data are available upon reasonable request to ADL through contact with LH (corresponding author). De-identified participant data might be available after the consent of all authors and the privacy policy office of the Universidade Cidade de São Paulo (UNICID).

Acknowledgements

Luiz Hespanhol received a Young Investigator Grant from the São Paulo Research Foundation (FAPESP), grant 2016/09220-1. Tie Parma Yamato received a Young Investigator Grant from the São Paulo Research Foundation (FAPESP), grant 2017/17484-1.

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