Design and milling manufacture of polyurethane custom contoured cushions for wheelchair users

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RESEARCH

Please cite this paper as: Silva F, Beretta E, Prestes R, Kindlein W. Design and milling manufacture of polyurethane custom contoured cushions for wheelchair users. AMJ 2011, 4, 9, 500-506.
http://doi.org/10.21767/AMJ.2011.963

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Abstract

Background

The design of custom contoured cushions manufactured in flexible polyurethane foams is an option to improve positioning and comfort for people with disabilities that spend most of the day seated in the same position. These surfaces increase the contact area between the seat and the user. This fact contributes to minimise the local pressures that can generate problems like decubitus ulcers. The present research aims at establishing development routes for custom cushion production to wheelchair users. This study also contributes to the investigation of Computer Numerical Control (CNC) machining of flexible polyurethane foams.

Method

The proposed route to obtain the customised seat began with acquiring the user's contour in adequate posture through plaster cast. To collect the surface geometry, the cast was three-dimensionally scanned and manipulated in CAD/CAM software. CNC milling parameters such as tools, spindle speeds and feed rates to machine flexible polyurethane foams were tested. These parameters were analysed regarding the surface quality. The best parameters were then tested in a customised seat. The possible dimensional changes generated during foam cutting were analysed through 3D scanning. Also, the customised seat pressure and temperature distribution was tested.

Results

The best parameters found for foams with a density of 50kg/cm^3 were high spindle speeds (24000 rpm) and feed rates between 2400–4000mm/min. Those parameters did not generate significant deformities in the machined cushions. The custom contoured cushion satisfactorily increased the contact area between wheelchair and user, as it distributed pressure and heat evenly.

Conclusion

Through this study it was possible to define routes for the development and manufacturing of customised seats using direct CNC milling in flexible polyurethane foams. It also showed that custom contoured cushions efficiently distribute pressure and temperature, which is believed to minimise tissue lesions such as pressure ulcers.

Key Words

Custom contoured cushions, CNC machining, Three-dimensional scanning.

What this study adds:

1. Alternative route for custom cushion production to wheelchair users.
2. Investigation of CNC machining of flexible polyurethane foams.
3. Evaluation of pressure and temperature distribution to prevent tissue lesions such as pressure ulcers.

Background

Individuals with severe disabilities who cannot walk could spend their entire lives in a wheelchair. This device can increase mobility, autonomy, comfort and safety when well prescribed.[1] However, bad positioning in the wheelchair can lead to sitting-induced problems such as rigidity, contractures, deformities, movement restriction, and tissue lesions like pressure ulcers, and affect the user's emotional and intellectual development.[2]

Pressure ulcers frequently occur in people with disabilities and limited mobility who need to be seated in the same position for most part of the day. It is estimated that the United Kingdom spends between £180 and £321 million

(0.4–0.8% of healthcare spending) annually on pressure ulcer treatments, of which 36 to 50% result from wheelchair use.[3] In the United States, 2 to 23% of hospitalised patients present pressure ulcers[4] and 5 to 10% of wheelchair users have one episode of pressure ulcer per year.[5] The annual cost of pressure ulcer treatment in the US ranges anywhere between $1.68 billion to $6.8 billion, more than 1% of the total US healthcare budget.[6] These facts make pressure ulcer prevention an important health care issue both socially and economically.

Users with serious deformities need customised seats to maintain vital functions and comfort. Several solutions have been proposed with a specific focus on the modification of support surfaces for both geometry and mechanical characteristics of the contact area.[3, 7] Modifications in the support surface geometry can increase the contact area and therefore, reduce the pressure over the seat. This study understands that the manufacture process of a customised seat must be automated. On this account, it is necessary to ensure that the manufactured seats contour the user's anatomical surface with maximum contact. Geometrical distortions can result in unwanted forces and cause system inefficiency. This is the problem presented by most current practices that use a handmade process to manufacture the seat cushions.

In this sense, this study provides a technologically and economically viable alternative to manufacturing custom contoured cushions. It aims to obtain the user's geometry through a plaster casting, followed by a three-dimensional (3D) scanning of the accomplished cast.

Subsequently, the cushion is produced by CNC milling directly in flexible polyurethane foam block.

In the literature, few studies on flexible polyurethane foam machining have been reported. In earlier research, Brienza[8] proposed a specific machine for foam milling with a simpler construction and at relatively lower cost. Jouaneh, Hammad and Datseris[9] developed equipment to manufacture automobile seats using specialised hot wire tools. In the process developed by Olari and Allen[10], the flexible foam is treated by soaking it with a liquid and freezing the liquid. The hardened foam is machined. The foam is then returned to its original state. Other methods to harden the foam are liquefied gases, such as liquid nitrogen and carbon dioxide. In all reported cases, the foam is machined just after being temporarily hardened and left to return to its original flexible state.

In a study carried out by Shih, Lewis and Strenkowski[11] on the end milling of elastomers, different tools, spindles speeds and feed rates were tested to determine the best cut to those materials. A similar study was proposed to select cut parameters for polyurethane foam machining.

Even with the developed equipments, all of them are specific and require specialised tools, which limit custom cushion manufacturing all over the world. Therefore, this study aims to contribute to the investigation of CNC milling of flexible polyurethane foams.

Method

A study was carried out with a user with no physical restrictions to determine the parameters for CNC machining of flexible polyurethane foams. The study also analysed if the manufactured customised seat equally distributed the user's temperature and pressure.

A usual technique for the immobilisation of body fractures was applied to produce the cast. Fabric bandages saturated with dehydrated calcium sulphate ($CaSO_4$) were used as cast material. The fabric bandages were hydrated with water and placed on top of a 26kg/cm^3 density foam. This low density was chosen to copy the user's contour as it deforms easily. The user was placed on top of the foam in a folding wheelchair with footrest. A physiotherapist properly positioned the user until the cast was sufficiently dry and would not deform. This process can be seen in Figure 1.

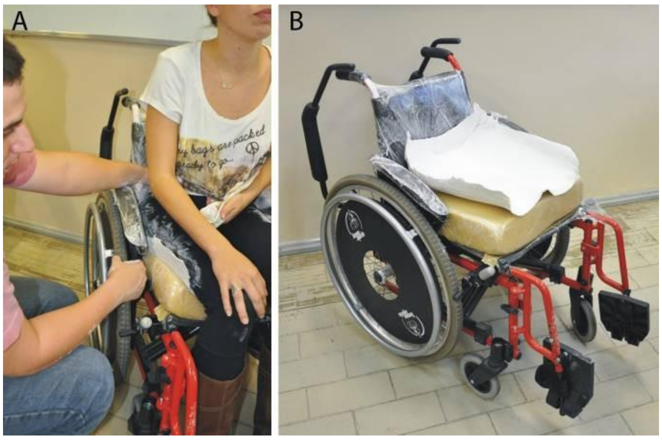

Figure 1: (A) User positioned in the wheelchair with adequate posture; (B) cast obtained.

The cast was then scanned three-dimensionally. Digitising systems are widely used to capture 3D data as they can obtain surface details with great precision. The equipment used was a laser scanner Konica Minolta Vivid 9i that operates with a triangulation measurement principle. This study used a 0.2 precision wide lenses. The point cloud data was imported into Geomagic Studio reverse engineering software. The data was processed and turned into polygon meshes and surfaces compatible with CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) systems. The final file is a data source to machine the user's geometry on foam. Although this method involves a more sophisticated technology, it presents some advantages, such as allowing digital storage and data transfer without losing information or occupying physical space. Therefore, an identical copy of the seat can be manufactured later or in another place, through any CNC machine. A virtual seat surface was then imported in Edgecam CAM software where the tool paths were calculated (Figure 2).

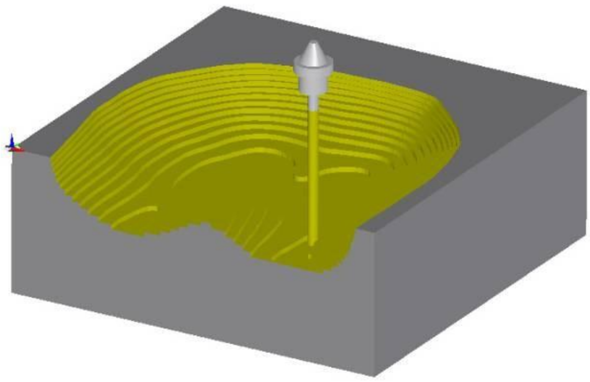

Figure 2: Programming of milling operation for roughing process.

A previous study was proposed to select cut parameters for polyurethane foam machining. It focused on foam with 50kg/cm^3 density, which was more adequate for the user's weight support. The study was based on the investigation carried out by Shih, Lewis and Strenkowski.[11]

Two cut directions (climb and conventional), four spindle speeds (from 6000 to 24000rpm) and 10 feed rates (from 400 to 4000mm/min) were tested. The best parameters were selected and then applied in a further study. Afterwards, three seats with spindle at 24000rpm and a combination of feed rates for roughing and finishing (from 2400 to 4000mm/min) were machined. For the roughing operations, an end mill Dormer C167 was used, and for the finishing operations, a ball nose mill Dormer C502. Both tools were 30° doubled-flute mill, High Speed Steel with 6mm diameter. A milling unit was set in Tecnodrill Digimill 3D CNC equipment to be used for the process. The maximum cut depths were 10mm for roughing and 6mm for finishing. It should be observed that the cut depth was limited by the cutting tool length since the polyurethane foam demanded low cut forces.

The seats were 3D scanned for dimensional analysis. The equipment was the same used to scan the user's cast. The data was processed in Geomagic Studio software. It generated a three-dimensional polygonal mesh that was transferred to Geomagic Qualify software for comparison. This comparison was made between the 3D mesh from the user's cast and the 3D mesh from the machined seats. This data showed which parameters were more adequate to generate precise seat geometry. The surfaces were also visually analysed and factors such as burrs, imperfections and uniform surfaces were taken into consideration.

An analysis of pressure distribution was made to obtain data that could evaluate whether the customised seat was distributing the user's weight evenly through the surface. It can indicate if dimensional distortions made during milling process will affect the pressure distribution significantly. The equipment used to measure pressures was FSA Pressure Mapping by Vista Medical. It consists of a mat with 256 sensors that measure pressure points and generates a graphic to visualise the results. For this test, the mat was placed between the customised seat and the user, who was positioned in an adequate posture by a physiotherapist.

Another factor that is believed to influence the user's comfort is temperature. Therefore, a thermographic analysis was made to verify if these seats could also help to distribute the temperature evenly over the surface. A thermograph SAT HY6800 was used. It measures the infrared energy (heat) emitted by the surface. The user was seated on a chair and relaxed for 20 minutes to become thermo-equilibrated in the laboratory space. The physiotherapist then positioned the user in the custom cushion where he remained seated for 20 minutes to stabilise temperature.[12, 13] Afterwards, the user was removed from the cushion and the surfaces were thermographed.

Results and Discussions

The user's casting was relatively simple to be made and with low costs as expected. The three-dimensional scanning process took just a few minutes (for one piece), including the equipment setup. This study verified factors related mainly to the milling process. Therefore, it was not necessary to test the cushion with a disabled user.

According to the preliminary studies, there is a great influence by the cut direction, i.e. climb (Figure 3A) or conventional (Figure 3B). The climb milling generated a discontinuous chip that would occasionally get stuck on the tool. It formed a built-up-edge and pulled away pieces from the material. It also generated a very rough surface with burr-type debris attached to the work piece. The conventional milling generated a ribbon chip. This milling type is not usually desirable in metal's milling but for polyurethane foams, it generates a clear cut. The only observation about this chip is that sometimes it can get clogged in the tool and damage the finishing. Therefore, the cut direction used in the next milling studies was conventional, both for the roughing and finishing processes.

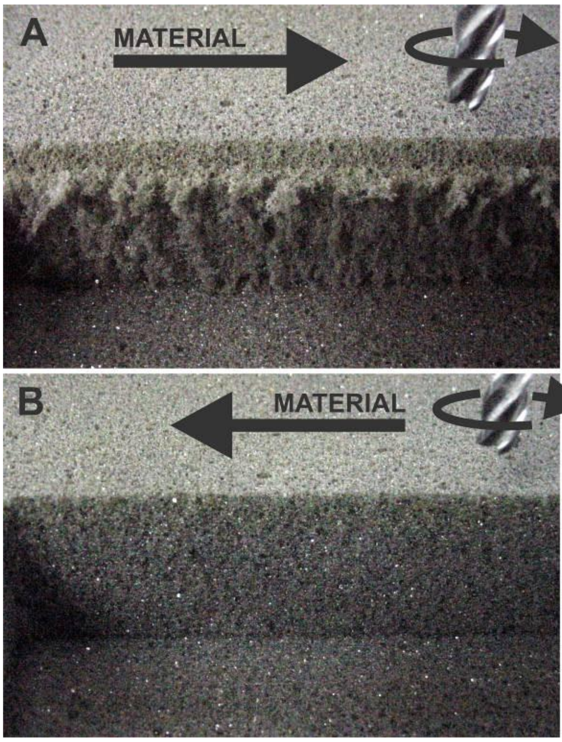

Figure 3: (A) Climb cut and (B) Conventional cut surfaces

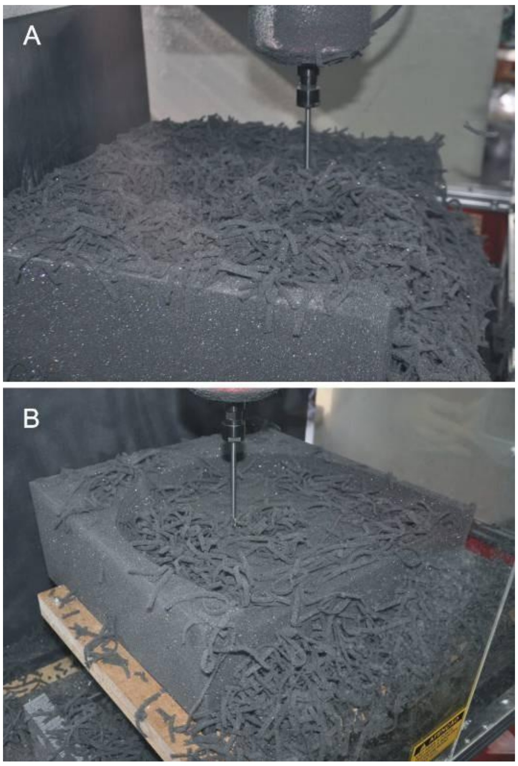

Figure 4: Generated chips in the roughing process with (A) 2400mm/min and (B) 4000mm/min feed rate.

The generated chips were one of the factors considered for the CNC milling evaluation. When machined at 4000mm/min feed rate, the generated chip was a long ribbon type (Figure 4B). As they are long, from time to time they can get clogged in the tool and be expelled violently. This factor could damage a piece with thin walls. It can also damage the tools or increase the risk of harm to the machine operator, but it is not probable due to the material hardness. When roughing was done at 2400mm/min feed rate, the obtained chips were smaller. However, they accumulated in the cut area (Figure 4A). The finishing at 2400mm/min feed rate resulted in a clean surface while at 4000mm/min feed rate, some scallops remained in the piece.

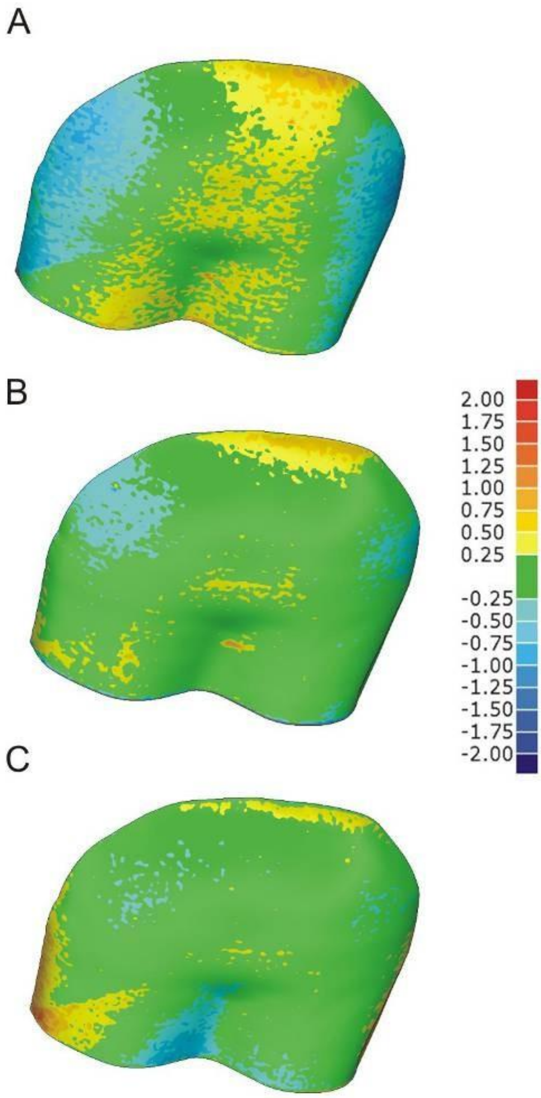

Figure 5: Dimensional comparison of machined custom cushions (Roughing/Finishing feed rate). (A) 2400/4000, (B) 4000/2400 and (C) 4000/4000 mm/min.

The dimensional analysis was made and a major deformation was found in the seat with roughing at 2400mm/min and finishing at 4000mm/min feed rate (Figure 5). These deformities occurred in the central portion of the piece and even bigger distortions in its walls. However, the areas that deformed the most showed a difference lower than 2mm.

Considering the small deformations, the best results were determined due to the process time. Thus, the parameters selected were roughing at 4000 and finishing at 2400mm/min feed rate. Figure 6 shows the custom contoured cushion before the final fabric lining and the wheelchair adaptation.

Figure 6: Custom contoured cushion before the final fabric lining and the wheelchair adaptation

The pressure distribution tests showed that these seat deformations did not alter the user's weight distribution. The standard wheelchair seat was also tested. It showed that pressures accumulated in the user's ischial tuberosities (Figure 7A). On the other hand, the customised seats distributed the pressure more evenly (Figure 7B). It was considered that these seats could benefit the user's positioning. This factor could minimise the probability of pressure ulcers. By considering the pressure distributions only, all the milling parameters were adequate for the manufacturing of these cushions.

The thermographic analysis showed that the temperature in the customised seats was better distributed when compared with the standard ones (Figure 8). It did not present points where the temperature was accumulated. The standard seat presented temperature peaks. The graphics showed the temperature in degrees Celsius in the vertical axis (top to bottom) and in the L01 and L02 line extension traced in the cushions. According to the lines L01 and L02 in Figure 8A, some major thermal differences can be verified between both sides of the seat (red line corresponds to L01 and blue line corresponds to L02). However, in the custom cushions the pressure distribution was similar in all three seats, as shown in Figure 8B.

The tests demonstrated that the custom cushions had satisfactorily increased the contact area between the foam surface and the user. The standard seat showed areas where the contact was concentrated, generating more heat beyond pressure.

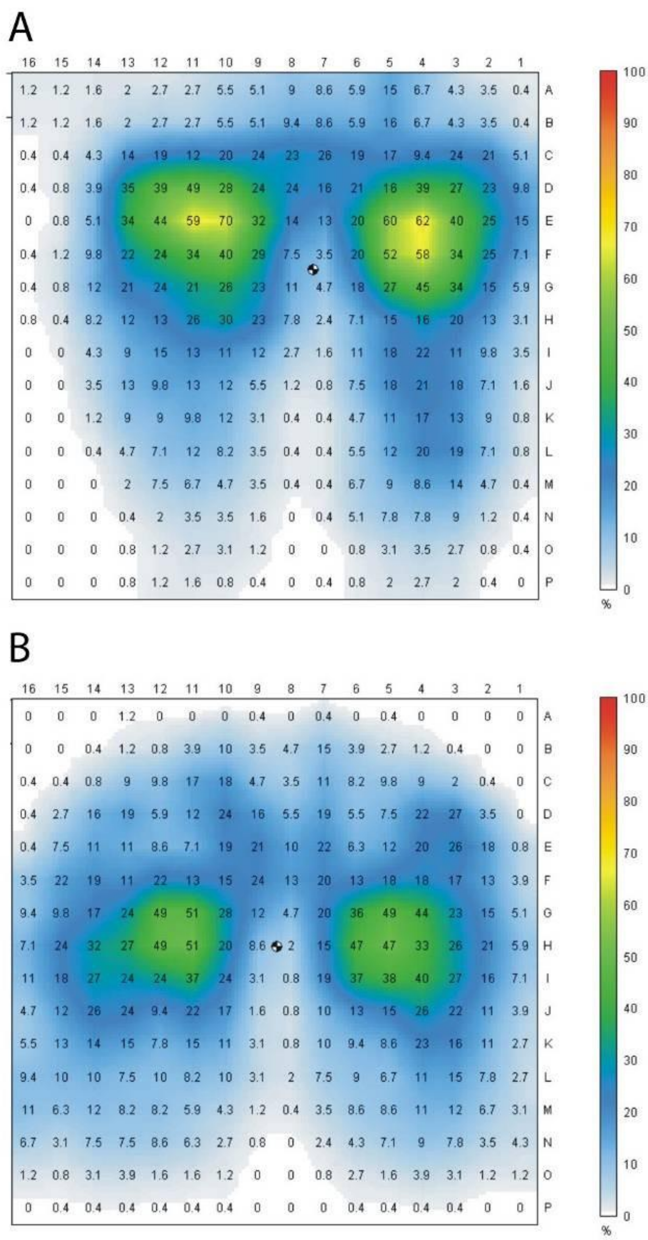

Figure 7: Pressure distribution. (A) Standard seat, (B) Customised seat

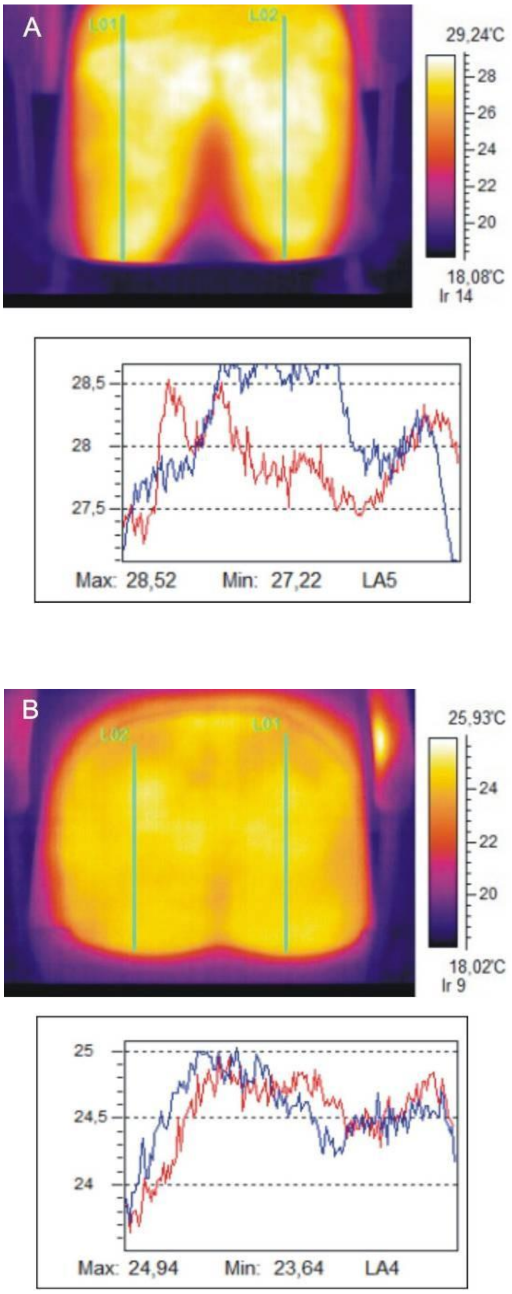

Figure 8: Thermographic analysis. (A) Standard seat and (B) Customised seat.

Conclusion

This study contributed with a manufacturing route for custom contoured cushions. It defined the parameters to seat machining with the use of conventional equipments and tools. Therefore, it was possible to define routines for the design and manufacturing of customised seats using direct CNC milling in flexible polyurethane foams. It generated minimal dimensional distortions and good finish. Thus, this factor indicated that the main objective of the cushion – to increase the contact area – was achieved. Throughout the analysis, the proposed customised seat provided adequate positioning and minimised pressure peaks and temperature concentration.

This study also showed that it is possible to develop customised products to satisfy the specific necessities of individuals with disabilities by providing quality cushions to the final user.

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PEER REVIEW

Not commissioned. Externally peer reviewed

CONFLICTS OF INTEREST

The authors declare that they have no competing interests.

FUNDING

CAPES, MEC/SESu.

ETHICS COMMITTEE APPROVAL

Not applicable