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Designing Ergonomic Safety Boots for Sustainable Construction in Botswana: A Case Study of Worker Foot Health

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ABSTRACT

The most essential asset in every construction work is the workers. In this regard, sustainability in construction must include and be centred on this vital resource. However, research indicates that civil engineers and construction workers often advocate for sustainability in infrastructural developments. This critical asset in construction often needs more consideration when people are engaged in construction work despite the many ergonomics challenges widely reported in the industry. This leads to workers in this industry being grossly afflicted by injuries such as musculoskeletal disorders, particularly of the foot. In addition, changes in global temperatures, attributed to global warming, situate civil engineers and construction workers, as they often work in open and challenging terrains, at risk of heat-related illnesses such as heat hyperpyrexia and heat exhaustion, which may also aggravate these musculoskeletal disorders conditions. However, it is pretty disturbing to notice that such illnesses are less investigated, particularly musculoskeletal disorders of the feet, which may be exasperated by the dire heat conditions noticeable in Botswana. This is because there is often a need for more knowledge and understanding of the risks associated with musculoskeletal disorders (MSDs). Furthermore, expertise in ergonomics is limited to assisting in the design of work as well as its conditions. This bequeaths both civil engineers and construction workers to operate under very challenging conditions despite pursuance of sustainability. Therefore, this case study investigated the prevalence of musculoskeletal disorders of the feet in the construction industry in Botswana with the purpose of designing a safety boot that matches the anthropometric measurements of the construction workers' feet. The research culminates in the design of a safety boot that is based on the workers' anthropometric measurements to prevent the occurrence of MSDs. The results of the study indicate that workers in this industry suffer from toe bunions, cons, toe deformities, smelly feet, etc. The study additionally indicates foot size differences across Botswana's tribes. These differences may have severe implications for the use of safety boots and the development of ergonomics illnesses, mainly since the current safety boots used are imported from elsewhere with no modification to address the anthropometric feet measurements of Batswana. It is anticipated that the research will provide the necessary awareness that can help civil engineers explore sustainability not only from the context of infrastructural development (objects) but also from the perspective of workers (humans). This underscores the need for further research and action in this critical area.

Keywords: Construction Worker Ergonomics, Musculoskeletal Disorders, Safety Boot Design, Anthropometric Measurements, Heat-related Illnesses, Sustainable Construction Practices

INTRODUCTION

Ergonomics, the science of designing and arranging workplaces, products, and systems to fit the people who use them, plays a crucial role in enhancing productivity, safety, and comfort. In the context of the construction industry, ergonomics is particularly significant due to the physically demanding nature of the work, which often involves manual labour, heavy lifting, and prolonged periods of standing or walking. In Botswana, the construction industry is a crucial driver of economic growth, contributing significantly to infrastructure development. However, the sector faces challenges related to worker safety and health, particularly concerning the use of safety boots that may need to meet ergonomic standards. This study focuses on the ergonomic challenges associated with safety boots and their impact on construction workers in Botswana. The motivation for this study arises from the increasing recognition of the importance of worker safety and well-being in achieving sustainable infrastructural development. Despite advancements in construction technologies and practices, the industry continues to grapple with high rates of work-related injuries and musculoskeletal disorders. In

Botswana, construction workers often need help with safety boots that are uncomfortable, poorly fitting, and inadequate in protecting against hazards. Addressing these ergonomic issues is crucial not only for improving worker health and safety but also for enhancing productivity and job satisfaction. By examining the specific challenges related to safety boots, this study aims to contribute to the broader goal of sustainable infrastructural development in Botswana. The primary objectives of this study were to:

- Investigate the ergonomic challenges faced by construction industry workers in Botswana, with a specific focus on safety boots.
- Assess the impact of these challenges on worker health, safety, and productivity.
- Identify the factors contributing to ergonomic issues in the design and provision of safety boots.
- Provide recommendations for improving the ergonomic design and availability of safety boots to enhance worker safety and well-being.

The paper is structured as follows: (i) a literature review of existing research on ergonomics in construction, focusing on the role of safety footwear, common ergonomic issues, and their impacts on worker health and safety; (ii) a description of the research methods used to gather data on the ergonomic challenges faced by construction workers in Botswana, including surveys, interviews, and observational studies; (iii) presentation the results of the study, discussing the specific ergonomic challenges related to safety boots, their causes, and their effects on worker safety and productivity; and (iv) summarises the key findings of the study, emphasising the importance of ergonomic safety boots for sustainable infrastructural development and the steps needed to improve worker safety and well-being in Botswana.

Literature review

According to the US Bureau of Labour Statistics (2018), the Construction Industry ranks fourth among the most dangerous industries in the United States of America after Transport, Installation Maintenance and Repair and Agriculture. The industry is reported to have an incident rate of 127.3 per 10,000 full-time employees. This is based on a variety of roles associated with construction work, which ranges, for example, from building to heavy and civil engineer constructors. It is reported further that workers in this industry use dangerous equipment and tools, are exposed to hazardous material and are sometimes required to work on elevated vicinities in confined spaces. However, in the midst of all this seemingly dangerous landscape is the use of the safety boots. The use of safety boots is intended to keep construction workers safe from potential foot injuries.

Despite the critical role safety boots play in the construction industry, research on the effects of safety boots on users appears to be scanty, particularly in countries such as Botswana, which are still struggling to establish their position on the issue of sustainability for both workers and infrastructural developments. Nevertheless, where there has been evidence of research, such work dwells on the protection offered by the safety boots from interferences or hazards from the external environment. Minimal regard is given to what goes on within the safety boot itself when worn. Oschsmann et al. (2016) concur with this view. For example, in their study to look at the influence of different safety boots on gait and plantar pressure in the automotive industry, Oschmann et al. (2016) opined that the overall function of safety boots is chiefly based on the avoidance of injury in case of an industrial accident. The authors proceed further to assert that safety boots must also be seen as a long-term preventative instrument for maintaining the health of employees, particularly in preventing Musculoskeletal Disorders, as they can affect users' gait parameters.

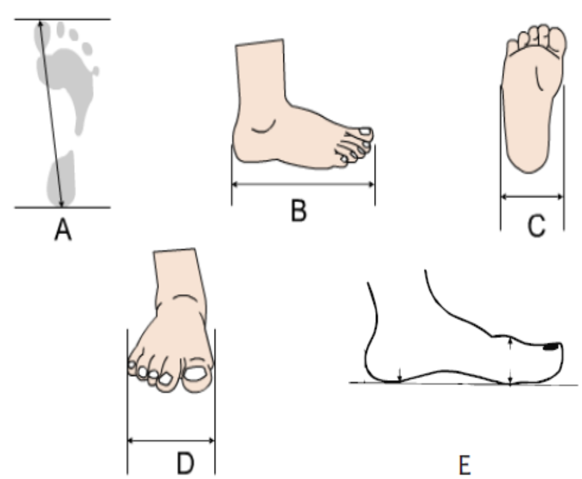
Additionally, research shows a variety of injuries that may be caused by Occupational footwear. For example, Barigga et al. (2024), Dobson et al. (2017), Orr et al. (2022), and Dumbhare et al. (2022) reviewed the literature on the injuries caused by occupational footwear. They found that inappropriate footwear can cause injuries to the foot and other related bone structures with calluses, nail injuries (ingrown) and plantar fasciitis or bursitis. On the other hand, Dobson et al. (2017) conducted a systematic review of the literature on occupational footwear. They concluded that work safety boots design affects the way the worker walks (gait), observing that safety boots are often designed for occupational safety at the expense of comfort. The issue of gait as a problem is also captured by Orr et al. (2022). In their study, they also found occupational footwear to impact gait, angular velocity, joint ranges of motion, posture and balance, heart rate, temperature, muscle activity and selected occupational tasks. Furthermore, Dumbhare et al. (2022) conducted a study to determine the prevalence of foot problems associated with wearing safety footwear in factory employees wearing footwear for prolonged periods. In this study, the researchers found that 62.5% of workers suffered from plantar fasciitis while 30% had dead skin (corns), 12.5% reported having blisters/swelling on the foot and bunion (bulge) on the joint at the base of the big toe. The study showed a significant prevalence of foot problems caused by wearing safety footwear.

Of relevance to this study is the sustainability goal of incorporating ethical human considerations in construction, the achievement of which is notably dependent on the application of ergonomics. According to the joint document by International Ergonomics Association (IEA) and the International Labour Organisation (2019), Ergonomics is the branch of science dedicated to studying how people interact with other components of a system. In order to maximise both total system performance and human well-being, this profession also applies theory, principles, data, and methodologies to design. The understanding of ergonomics is expected to facilitate the design of products, tasks and environments that fulfil the user's physical and cognitive requirements (Nadadur et al., 2012). Furthermore, ergonomics advances the goal of and recognition of human variability and, as such, could play a significant role in helping construction and civil engineers design products, tasks and environments that cater for this human variability, thus promoting sustainability in the industry. It is crucial to understand that the field of ergonomics is replete with techniques that can be used to address this sustainability goal. One such technique is to apply anthropometric (human body measurements) data of the local users in the design of safety boots for the construction industry in Botswana.

The authors argue that the construction industry in Botswana promotes the use of ill-designed safety boots that do not conform to the anthropometric measurements of local workers. This is premised on the fact that there is no local anthropometrics data bank to tap from, which can be used to influence the design of ergonomic safety boots for construction men and women workers in Botswana. Most of the available safety boots originate from outside Botswana (China, Australia, South Africa and the USA). In minimal situations where manufacturing is done locally, foot measurements and standards used to create safety boots are based on something other than the anthropometric data of locals but on users from safety boot's point of origin. Safety footwear is mandatory in the construction industry, and workers are usually engaged in an eight-hour day shift (Barriga et al., 2024). That means, as long as such vital data is not available, workers in the industry will continue to suffer from musculoskeletal disorders of the feet, making it difficult for the local construction industry to achieve sustainability when the very asset central to infrastructural development is not healthy.

MATERIALS AND METHODS

One way of achieving sustainability in this regard is to design safety boots based on the anthropometric measurements of construction workers in Botswana. When designing a product to interact with the human body, designers consider the size and shape of people. However, human sizes and shapes differ considerably across nations. Such variance is also evident in Botswana. In a demonstration of this variance, a pilot study was conducted that involved collecting anthropometric data from workers in construction companies in the main villages in Botswana. About 100 construction workers, comprising 82 males and 18 females aged 33-54, were randomly sampled and recruited from different districts of the country for involvement in the study. In addition, observations and interviews were also held, and relevant data was collected. Anthropometric data from five different dimensions of areas of the foot were obtained. The dimensions covered the foot length, ball of foot length, outside ball of foot length, foot breadth diagonal, heel breadth, navicular height, instep height and heel to malleolus. These dimensions are represented as A, B, C, D, and E in Figure 1.



POINT	MEASUREMENT
A	Long cross foot length
B	Foot length
C	MTP Width
D	Toes Width
E	MTPJ Height

Figure 1. Foot areas measured

After that, the data was processed with statistical software (SPSS) to determine the means, standard deviation, minimum and maximum values, as well as the 5th, 50th and 95th percentiles for each foot segment. The Pheasant & Haslegrave (2018) Protocols were used to collect data. In this regard, three measurements for each foot area measured were obtained, and later, an average was calculated to represent a specific foot area measurement. This was purely done to reduce the margin of error in data recording. From the data collected, about eight communities emerged in the study. These communities are captured in the research as TA, TB, TC, TD, TE, TF, TG, TH, TI and TJ. They are shown in Tables 1, 2, 3 and 4.

The data was later analysed to determine the 95%ile, and 5% being the two extremes (largest and smallest) of the user population relevant to the design of the safety boots for each of the foot areas measured. It was here necessary to use percentiles rather than averages as using averages may have severely disadvantaged users with more than average dimensions (i.e. half the users). These percentiles were then used to calculate the correct dimensions of the boot. For purposes of Intellectual Property (IP) the dimensions are not included in the paper. Furthermore, for ethical considerations, the authors used letters as references to tribes that emerged from the study. These are TA, TB, TC, TD, TE, TF, TG, TH, TI, and TJ. Table 1 shows differences in foot size for males, while Table 2 shows differences in female foot size.

Table 1. Largest male foot anthropometrics among community

Tribe		Measurement in (cm)				
		A	B	C	D	E
1	TA	31.0	11.3	6.9	6.1	9.1
2	TB	28.6	11.0	7.2	6.6	9.2
3	TC	26.8	10.9	7.4	6.3	8.4
4	TD	31.4	10.8	7.1	6.4	8.5
5	TE	31.0	11.3	6.9	6.1	9.1
6	TF	30.9	10.8	7.0	6.4	8.6
7	TG	30.1	10.5	6.9	6.3	8.0
8	TH	30.8	11.2	7.0	6.7	8.8
9	TI	30.2	10.9	6.9	6.4	7.9
10	TJ	29.6	11.1	6.5	6.2	8.8
	Average	30.0	11.0	7.0	6.4	8.6
	SD	1.41	0.25	0.23	0.20	0.45

Table 2. Smallest male foot anthropometrics among community

Tribe		Measurement in (cm)				
		A	B	C	D	E
1	TA	25.8	9.6	6.4	6.1	7.5
2	TB	27.0	9.9	6.7	6.2	8.1
3	TC	25.9	9.8	6.5	6.3	7.9
4	TD	29.5	10.0	6.9	6.5	7.4
5	TE	28.2	10.9	7.0	6.2	8.8
6	TF	24.8	9.3	6.0	5.6	7.4
7	TG	27.4	10.1	6.9	6.5	8.1
8	TH	30.2	10.4	7.2	6.7	8.8
9	TI	26.9	9.8	6.6	6.3	7.8
10	TJ	28.8	10.4	6.9	6.2	8.5
	Average	27.5	10.0	6.7	6.3	8.0
	SD	1.73	0.46	0.35	0.3	0.53

Table 3. Largest female foot anthropometrics among community

Tribe		Measurement in (cm)				
		A	B	C	D	E
1	TF	23.7	8.4	5.8	4.7	5.7
2	TG	24.1	8.7	6.4	5.3	6.1
3	TD	21.6	9.3	6.1	4.8	6.5
4	TB	21.4	9.0	6.0	5.2	6.1
5	TA	20.5	8.4	5.9	5.0	5.8
	Average	22.3	8.8	6.0	5.0	6.0
	SD	1.56	0.39	0.23	0.25	0.31

Table 4. Smallest female foot anthropometrics among community

Tribe		Measurement in (cm)				
		A	B	C	D	E
1	TF	17.9	9.2	6.2	5.2	6.7
2	TG	20.8	7.9	5.9	4.7	5.9
3	TD	20.4	8.0	5.8	5.0	5.7
4	TB	21.4	9.0	6.0	5.2	6.1
5	TA	19.6	8.7	6.4	5.4	6.6
	Average	20.0	8.6	6.1	5.1	6.2
	SD	1.35	0.59	0.24	0.26	0.44

RESULTS AND DISCUSSION

Foot-related injuries

Construction workers in Botswana often suffer from various foot-related injuries and illnesses. One common issue observed is the development of corns or calluses, which may develop from repeated friction and pressure on the skin, often caused by ill-fitting boots. There was evidence of workers wearing boots with loose soles and torn or softened heels (Figure 2). These compromised safety boots may not protect workers from dangerous materials on the ground, such as sharp objects and nails. The deterioration of these boots also increases the risk of slips, trips, and falls, further compromising workplace safety.

Symptoms of calluses were found on the underside of workers' feet, along with skin discoloration and damage. These symptoms not only cause discomfort but can also alter a worker's gait, potentially leading to musculoskeletal issues if left unaddressed.

Figure 3 illustrates damaged boot soles. In some instances, the soles seemed to peel off from the safety shoes. Such boots no longer offer adequate protection from injuries that can be caused by nails or other sharp objects on the ground. This level of damage also compromises the boot's ability to provide proper support and cushioning, which could contribute to fatigue and long-term foot health issues.

Figure 2. Worn-out boot in use.

Figure 3. Worn-out safety boot sole.

Feet dimension and design

The results of the study revealed differences in feet anthropometrics measurements across male workers and female workers. For example, the average cross-foot length for males is 30 cm (Table 1), while the average cross-foot length for females is 22 cm (Table 3). This accounts for a difference of 8 cm between males' and females' feet. The longest male cross-foot length measured a whopping 31.4 cm, while the longest female cross-foot length measured 24.1 cm. These differences were also apparent across the different communities in Botswana. For example, Community D (TD) accounted for the largest male cross-foot length, while Community G (TG) accounted for the longest female cross-foot length, and Community B (TB) accounted for the smallest cross-foot length (Tables 1, 2 and 3). As can be observed, one’s foot could be shorter in one dimension, while its other areas could be larger. For example, while Community D (TD) have the largest cross-foot length of 31.4 cm, they have a 10.8-foot length and 8.6 MTPJ less than TA and TB, respectively, as shown in Table 1. These differences can create severe challenges for designers, hence the use of percentile values and not average dimensions for the design. Furthermore, it was clear from the study that in this company, construction workers had foot-related injuries such as cons/calluses and bunions. Notably, 80% of the boots were worn out and had only been used for a period of three months. Some of the safety boots had their steel- caps exposed and their soles torn out. The same safety boots allowed water to penetrate the feet when worn and in contact with water. Furthermore, soil and mud accessed the inside of the safety boots, and the safety boots were found to be extremely heavy. In addition, workers generally wore worn-out safety boots, as shown in Figures 2 and 3. This is not surprising as some of the safety boots are used as regular shoes even beyond the legal eight-hour per day period of work. Equipped with this data, the researchers applied the University of Botswana New Product Development (UBNPD) process to design the safety boot (Figure 4). Inspired by the work of (Kotler and Keller, 2006), this approach also considers the socio-cultural context, sustainability considerations throughout the development process of a product and competencies needed in the model. It reflects on the design landscape to enhance sustainability (Rapitsenyane and Sserunjogi, 2023). The process in Figure 4 offers a structured approach through a five-phased design process (inquire, define, design, validate and deliver) in which sustainability is taken up at each phase (Moalosi and Rapitsenyane, 2023).

In this regard, sustainability is attained by applying anthropometric data to innovate an ergonomic safety boot, as depicted in Figures 4 and 5. The prototype has a pending design utility model to be granted by the Companies Intellectual Property Authority. Figure 6 depicts the prototype of an ergonomic safety boot designed using anthropometric data obtained from local construction workers.

Limitations of the study

The first limitation encountered centred on culture. Traditionally, in Botswana, it is taboo to require people to provide their foot measurements. This practice is associated with witchcraft referred to in the local language as 'go tsaa lonao' and interpreted to mean having information about one foot for witchcraft purposes. The researchers came across a lot of resistance as construction workers were initially reluctant to provide relevant data. The presence of foot injuries and disease symptoms did not help the situation either, as more workers had such health problems. For them to provide data, construction workers were required to reveal their injuries and wounds by removing their safety boots for data collection. Finally, as this was a design exercise meant to come up with an innovation, intellectual property issues were also a limitation, as some information and data would have to be held back before proper protection documents could be finalised.

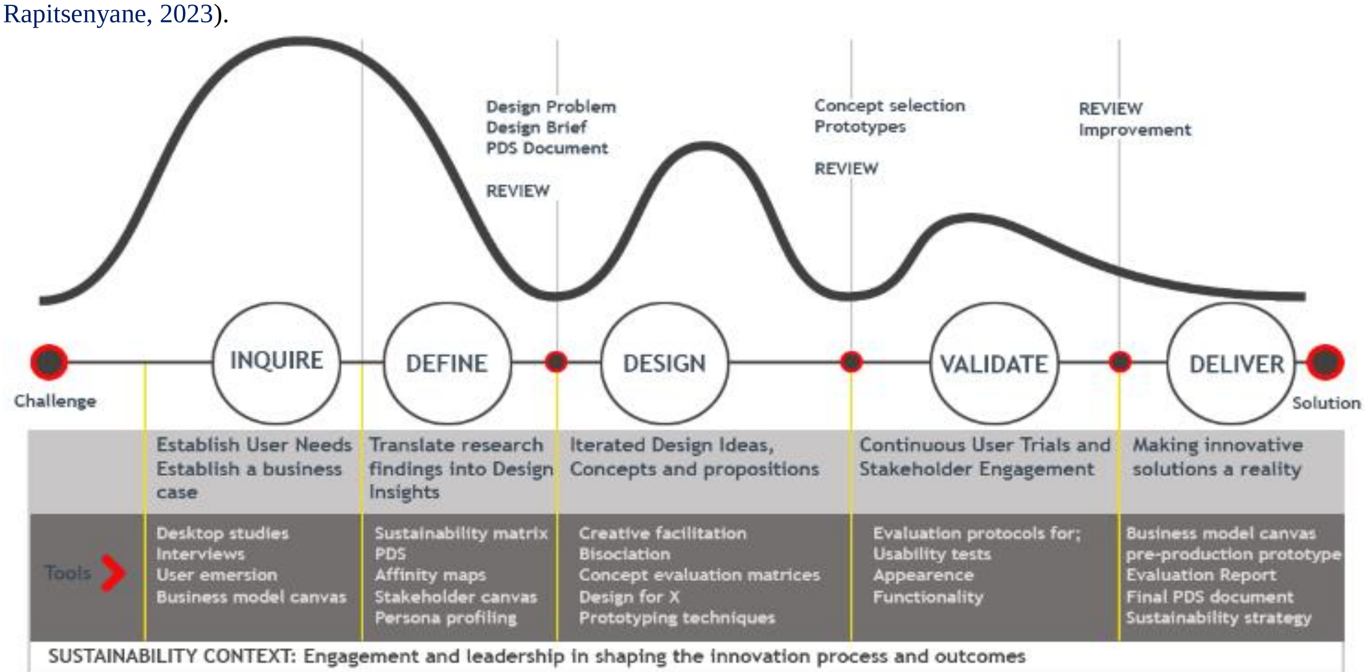


Figure 4. The University of Botswana New Product Development process (Moalosi and Rapitsenyane, 2023).

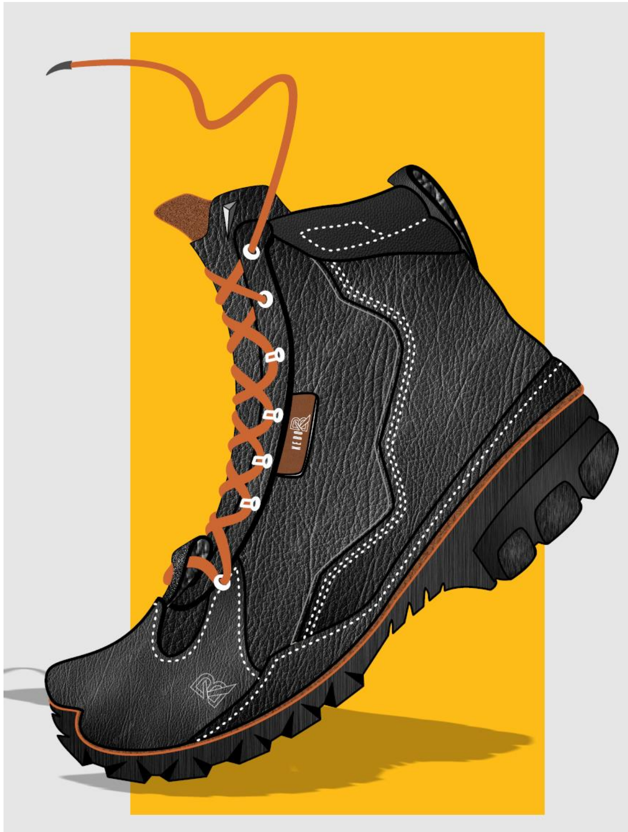


Figure 5. The designed safety boot

Figure 6. Ergonomic Safety Boot prototype for construction workers in Botswana.

CONCLUSION AND RECOMMENDATION

This study has highlighted the critical role of ergonomics in promoting sustainable infrastructural developments in Botswana, with a specific focus on the ergonomic challenges faced by construction industry workers due to safety boots. By investigating the ergonomic issues related to safety boots, we have underscored the significant impact these challenges have on worker health, safety, and productivity. The findings reveal that poorly designed safety boots contribute to discomfort, injuries, and reduced efficiency among construction workers, which, in turn, affects overall project outcomes and sustainability goals.

The objectives of this study were to explore the specific ergonomic challenges associated with safety boots, assess their impact on workers, identify contributing factors, and provide recommendations for improvement. Through detailed analysis of the data obtained from construction workers, the objectives were to provide valuable insights into the ergonomic shortcomings of current safety footwear and offer practical solutions for enhancing their design and availability. Ergonomics supports sustainability in many ways, as it can enhance health by reducing the risks of injuries and illness in the workplace. When designing a product to interact with the human body, designers consider the size and shape of people. However, human sizes and shapes differ considerably across nations. Such variance is also evident in Botswana. The safety boot designed based on anthropometric data demonstrates how such data can be used to protect people in the construction industry, and this is how sustainability in this context can be achieved.

Addressing the ergonomic needs of construction workers, particularly in the context of safety boots, will significantly improve worker well-being, reduce injury rates, and boost productivity. This, in turn, supports the broader goal of sustainable infrastructural development in Botswana, ensuring that construction projects are not only economically viable but also socially responsible and environmentally sound. Implementing the recommendations from this study can lead to better-designed safety boots that cater to the ergonomic needs of workers, thereby fostering a safer, healthier, and more productive construction industry.

To address the ergonomic challenges highlighted in this study, it is recommended to collaborate with footwear manufacturers to develop safety boots tailored to the specific anthropometric measurements of Botswana's construction workforce. Utilising local data will ensure a better fit, enhance comfort, and reduce foot-related injuries. Implementing training programs focused on the importance of proper footwear, foot health, and ergonomics can empower workers to make informed choices and promote a culture of safety. Additionally, adopting culturally sensitive data collection methods—such as indirect measurements or anonymised data gathering—can overcome barriers and facilitate the acquisition of accurate information necessary for designing ergonomic safety equipment.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Author's contribution

All authors contributed equally to this work.

Consent to publish

Not applicable.

Competing interests

The authors declare no competing interests in this research and publication.

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