An investigation into the cause of the inner dark areas and outer lighter areas (ghosting) seen in dynamically-created two-dimensional bare footprints

Abstract

Dynamic bare footprints differ from static bare footprints through the presence of additional, lighter markings around the rear of the heel print and apices of the toe print areas. These images can appropriately be described as inner dark and outer ghosting features. To date, the functional cause of both features has not been understood. To gain such an understanding could potentially allow the further development and use of these features in forensic identification.

The aim of this project was to investigate the causes of the inner dark and outer ghosting features seen in dynamic bare footprints through an observational, practice-based action research approach within a gait laboratory. Volunteer male participants provided bare footprints on inkless paper taped to a Kistler force plate with video cameras situated either side. Ground reaction force data were collected as the footprints were formed and the event recorded using video cameras to allow these data to be correlated later.

The findings suggest that the ghosting at the heel is the result of splaying of the fibro fatty pad, while that at the toes is the result of the distal ends of the toes coming into contact with the ground as the heel is lifted.

Footprint, ground reaction force and video data comparisons showed that the inner dark area of the heel print corresponded with the main body of the heel contacting the ground. Outer ghosting corresponded with a backward splaying of the fat pad and the heel strike transient spike in vertical ground reaction force during increased loading. The inner dark area of the toes corresponded with a longer period of toe contact with the ground. Outer ghosting corresponded with the decreasing vertical ground reaction force and shorter contact time as the toes were leaving the ground towards the end of the contact phase of gait.

Although the sample size was limited, these are new appreciations which could facilitate the use of the inner dark features in identification to provide additional points for comparison in cases involving dynamic bare footprints. Further work is now indicated to study these features in different populations and under varying conditions.

Keywords

Forensic; Bare footprint; Ghosting; Gait analysis.

1. Introduction

The term “bare footprints” refers to the marks made by the plantar surface of an unshod foot on a hard surface – a two-dimensional representation of a three-dimensional foot [1]. Bare footprints can be static or dynamic; static prints are associated with standing and dynamic prints with walking or possibly running. In recent times the forensic community has begun to consider the potential of bare footprints to show individuality [2-9]. Practitioners in various forensic science disciplines use bare footprints in identification including anthropologists, marks examiners, ridge detail analysts and podiatrists albeit from different perspectives. For the purposes of this article, the term ‘bare footprint’ refers to the shape and size of the footprint and not the ridge detail that might be present in these prints. Podiatrists consider bare footprint individuality to be the product of a complex relationship between functional anatomy of the lower limb (foot, ankle and leg) weight transfer between the foot and ground, and “body caricature” [10].

Interest in using bare footprints in identification has increased since the mid-1990s. Previous use of bare footprints in identification assumed that footprints are highly individual, possibly unique. This was tested by the Royal Canadian Mounted Police (RCMP) in a 10 year study [4,5,11,12] which indicated that footprints are highly individual. Subsequent to this work, the limits of knowledge regarding bare footprint form began to be questioned, through research [1] and Appeal Court judgements [13,14] suggesting a need for further studies in this area.

Bare footprint examination uses the ACE-V approach (Analysis, Comparison, Evaluation and Verification) [15]. For the comparison, crime scene footprints are compared with reference footprints from known persons [2]. The evidential weight of the comparison is stated – i.e. how strongly the matching and mismatching of features indicates that the prints are or are not from the same person [2].

Various techniques exist to enable the analysis and comparison of bare footprints, a number of which use lines drawn between recognizable areas of each print being compared [1,2,3,16].

Experience has shown that the dynamic form of bare footprints typically presents with two features not usually seen in static prints; namely inner dark and outer ghosting areas at the posterior (heel) and various anterior (toe) areas (Fig. 1). With the exception of Reel’s validation work [1], Burrow’s recent observations [17] and possibly Barker and Scheuer’s earlier work on bare footprint analysis [18], these features are not mentioned in any other past publications involving considerations of bare footprints [19]. As such, it is not known whether the inner dark or outer ghosting areas were used in much of the published research that has attempted to develop an understanding of the nature and behaviour of bare footprints under various conditions. Additionally there have been no previous investigations into what causes these inner dark and outer ghosting features. Such uncertainties are problematic when considering the use of bare footprints in the context of human identification as it is not known which areas are the most appropriate to be used when measuring bare footprints for comparison purposes. Methods used in forensic comparisons should be standardised, valid, reliable, controlled, error free and fit for purpose [19]. Ideally, these features need to be understood in order to support their use in practice. However, if these features simply relate to randomly created anomalies for example, further use in a forensic context could be inadvisable. Furthermore, while the measurement and comparison of the outer ghosting areas has been validated [1], the inner dark features of footprints have not been considered further.

Preliminary work was therefore indicated to investigate what causes the inner dark and outer ghosting features. Additional work would then consider how these features can be used in identification and what their operating parameters are. Such work has the potential to improve the evidential value of bare footprints and through greater understanding, to consolidate the use of these features in line with the demands for improved standards and governance in forensic practice [20,21].

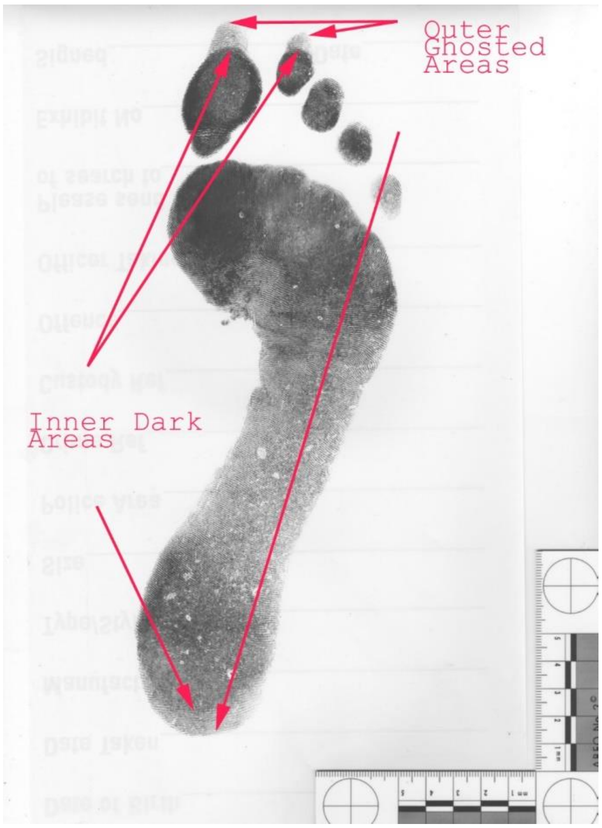

Fig. 1. Dark and ghosted areas seen in dynamic bare footprints

2. Materials and methods

2.1 Project aim

The aim of this project was to investigate the cause of the inner dark and outer ghosting areas which are frequently seen in dynamic bare footprints. The focus was therefore on functional print formation during the stance phase of walking, particularly the phases of loading response which occurs between initial contact (at the heel) and opposite toe-off, and pre-swing which occurs between opposite initial contact and toe-off as these are the phases where the inner dark and outer ghosting features are expected to form.

a. Ethics

Ethics approval for the work was granted by School of Human and Health Sciences, School Research Ethics Panel of the University of Huddersfield where the project work was carried out.

b. Methodology

The work carried out was exploratory and akin to the case study methodology described by Robson [22] although multiple case studies were used in this project. However, as the intention of the work was to inform and guide forensic podiatry practice, the overall project could be considered in its widest sense to be an action research project. The purpose of action research is to act as a tool for change [23,24], or more specifically as "a form of disciplined enquiry in which a personal attempt is made to understand, improve and reform practice" [25].

2.2 Materials/equipment

Multiple data were collected using an inkless bare footprint kit[1], a calibrated Kistler Force platform[2] and a Simi® motion digital video recording system used with two mvBlueCOUGAR® – X' high speed cameras recording at a default 100 frames per second (fps) (Fig. 2). The cameras were controlled by the Simi® software and video capture calibration was undertaken within the Simi software every time the cameras were moved. The high resolution, high frame rate video cameras allowed video-assisted observation with frame-by-frame playback during later observational analysis and comparison.

2.3 Working methods

An opportunistic sample of six male volunteers was recruited to provide dynamic bare footprints from left and right feet under controlled conditions. The volunteers were over 18 and less than 65 years of age, in good general health and by self-evaluation free from significant foot/gait disorders.[3] Participants and/or results were to be excluded if any undeclared gait-related disorder became apparent, where any deliberate attempts to alter gait were noted during data collection or where their feet were too large to fit onto the inkless paper or pad. This sample size was adequate to show what caused the investigated phenomena; no statistical analysis was

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[1] A commercially available product consisting of a mat impregnated with a colourless chemical [26] and sheets of coated paper allowing an image to form as a subject steps onto the mat, picking up and transferring the chemical to the paper, producing a clear and detailed bare footprint.

[2] Technology considered to the most accurate in its field which uses piezo-electric sensors and Bioware® software to record multiple data on dynamic forces occurring at the foot/ground interface [27].

[3] As podiatry students & staff only were involved, in all cases this self-evaluation was believed to be relatively expert. A visual assessment of all participants was also made by the project lead prior to their inclusion in the study.

to be undertaken. As the sample involved was greater than a single case study, it also had the potential to show whether the cause was consistent or not.

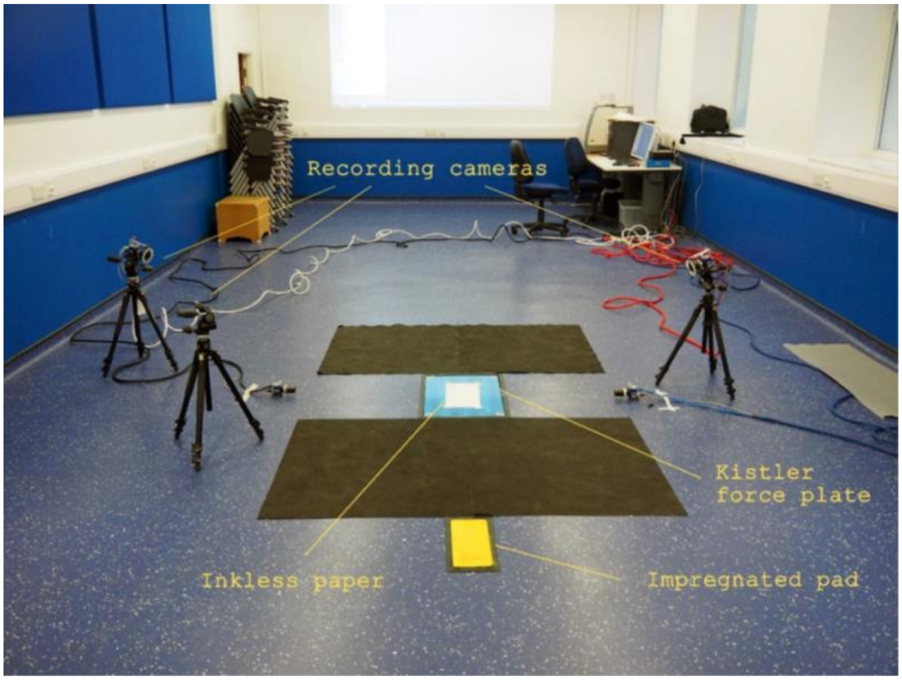


Fig. 2. Laboratory layout showing positioning of cameras, Kistler force plate and inkless paper kit

For each data capture, a sheet of impregnated paper from the inkless bare footprint collection kit was taped to the Kistler force platform. The digital video cameras were situated at floor level, each one 85cm from the centre of the force plate and 71cm from the edge of the inkless paper. This gave medial and lateral sagittal plane views of foot/ground interactions at initial contact and toe-off.

The collection of dynamic bare footprints was based on the method devised by Reel [1,28] and similarly described by DiMaggio and Vernon [2]. However, the method was adapted to incorporate a Kistler force platform and video recording equipment to capture the additional information necessary to explore the study's aims. Using a five metre walkway, a five-step protocol was utilised. This has been found to produce pressure and force values more in line with mid-gait protocols rather than one-step approaches, whilst still avoiding the targeting difficulties associated with mid gait protocols [29]. As the inkless pad and paper were being set up, each participant was asked to walk barefoot in the allocated area to help achieve their habitual gait prior to footprint collection. Beginning at a common starting point, the participant was asked to walk forward at their usual pace using their right foot to take the first step. The impregnated mat was placed alongside the approximate position of the participant's second step with their right foot. The inkless paper was placed alongside the approximate position of the participant's third step with their right foot. The walking cycle was repeated with the mat and paper positions being adjusted to match the 2nd and 3rd right step positions. If the participant's 3rd right step was not adjacent to the force platform, the start position was adjusted accordingly. The mat and paper were then taped into place (with the paper overlying the force platform). Prior to the walking cycle being repeated, the force platform and video equipment were started to record the interaction between foot and paper as the dynamic bare footprint was formed. The participant was then asked to repeat the walk to enable their 2nd right step to contact the mat and their 3rd right step to contact the paper (and underlying force platform). The laboratory technician assessed the force platform data and video recordings immediately after footprint capture to confirm that these were of acceptable quality. If the captured footprint was spoiled (e.g. through not landing within the confines of the mat and/or paper) or if the technician confirmed that there had been a data capture problem the process was repeated until the footprint and associated data had been captured correctly. The process was then repeated for the capture of data for the left foot.

The recording equipment provided data to allow an in-depth analysis of the foot/ground interaction [30] during the bare footprint capture. This enabled the events that occurred when the ghosting and the inner dark areas were formed in dynamic bare footprints to be captured and analysed. All data collected via the digital capture systems were linked through coded identifiers to each anonymised participant.

The data collected during the formation of participants' dynamic bare footprints included:

- Bare footprints showing inner dark and outer ghosting features, of posterior (heel) and anterior (toe) areas.
- Digital video recordings of the stance phase of gait of the participants to show the relationship between foot movement and the foot/ground interaction as the inner dark and ghosting features of posterior (heel) and anterior (toe) areas were being created.
- Ground reaction forces (vertical force (Fz), anterior-posterior force (Fy) and medial-lateral force (Fx)) occurring as the inner dark and outer ghosting features of posterior (heel) and anterior (toe) areas were being created.
- Temporal collation and observation of all data to show what was happening when the features of interest were being created.

In order to validate information, improve data quality and enhance the accuracy of findings with a view to enhancing the credibility of the work [22], the project utilised a basic form of analyst triangulation [31] whereby observations were made from the recordings by the project lead and the human movement laboratory technicians independently.

3. Results/findings

For the main data collection phase, six participants had been recruited. On the day an additional participant presented for data collection. Having met the inclusion criteria this additional participant was accepted into the study, providing data from seven subjects in total. Seven left and seven right footprints were obtained from the participants. Most footprints showed two-dimensional representations of the heel, mid-foot, ball of foot and five toes. However, 5th toe prints were not observed in two of the footprints. This correlated with these toes failing to contact the ground (paper) during the stance phase of gait. All collected footprints showed the outer ghosting and inner dark area features at heel and toe print areas (Fig. 3).

Bare Footprint Code*	Associated Prints	Bare Footprint Code*	Associated Prints
11156515L		11156515R	
11456515L		11456515R	
12006515L		12006515R	

Fig.3. Selection of prints collected from participants

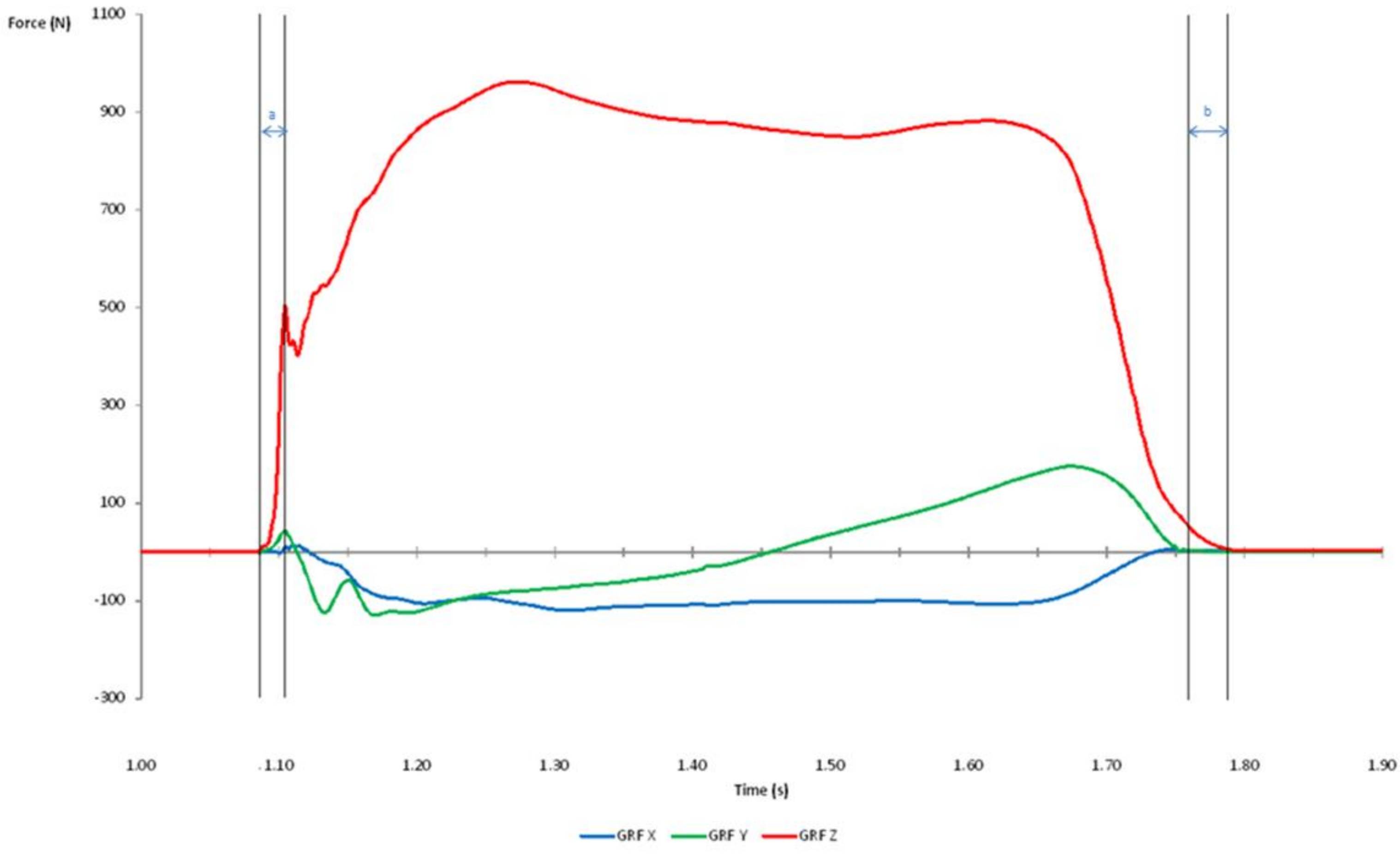
3.1 Description of vertical ground reaction force-time graphs for all prints

All ground reaction forces were sampled at 1000Hz to capture information relevant to the creation of the features of interest. Although data were collected for all three components of ground reaction force (Fig. 4), only the vertical ground reaction force was analysed for the purposes of this study. The vertical ground reaction force graphs for both feet of all participants showed:

- A rapid increase in force commencing at initial contact.

- A heel strike transient spike.
- After the heel strike transient spike, a steady increase in force creating the first force peak.
- A slight reduction from the force peak.
- A second force peak.
- A steady decrease in force culminating at toe-off.

In nine of the graphs a second heel strike transient spike was seen between the initial spike and the first force peak. In all but one graph, this second heel strike transient spike was relatively small compared with the first heel strike transient spike.



a - Ghosting observed in heel print

b - Ghosting observed in toe prints

Fig. 4. Example of ground reaction force/time graph (Subject 11156515L)

3.2 Description of the digital video recordings taken for all prints

The digital video recordings were sampled at 100Hz and showed medial and lateral sagittal plane views. All the subjects exhibited the expected sequence of events during the stance phase of gait in terms of the relationship between the foot and the ground. All the recordings showed the following relationship between foot and ground:

- Initial contact (Fig. 5).
- Distortion of the fibro fatty pad of the heel during the loading response (Fig. 6).
- Progressive and increasing contact between the distal aspects of the foot and ground.
- Heel lift.
- Progressively increasing angle between the apex of the 1st toe (and all other visible toe apices) and ground as the foot progresses towards toe-off (Fig. 7).
- Toe-off (Fig. 8).
- No forward movement of the apices of the toes relative to the ground (dragging) observed.

Fig.5. Example of heel contacting the ground (Subject 11156515L)

Fig. 6. Example of heel splaying of fat pad (Subject 11156515L)

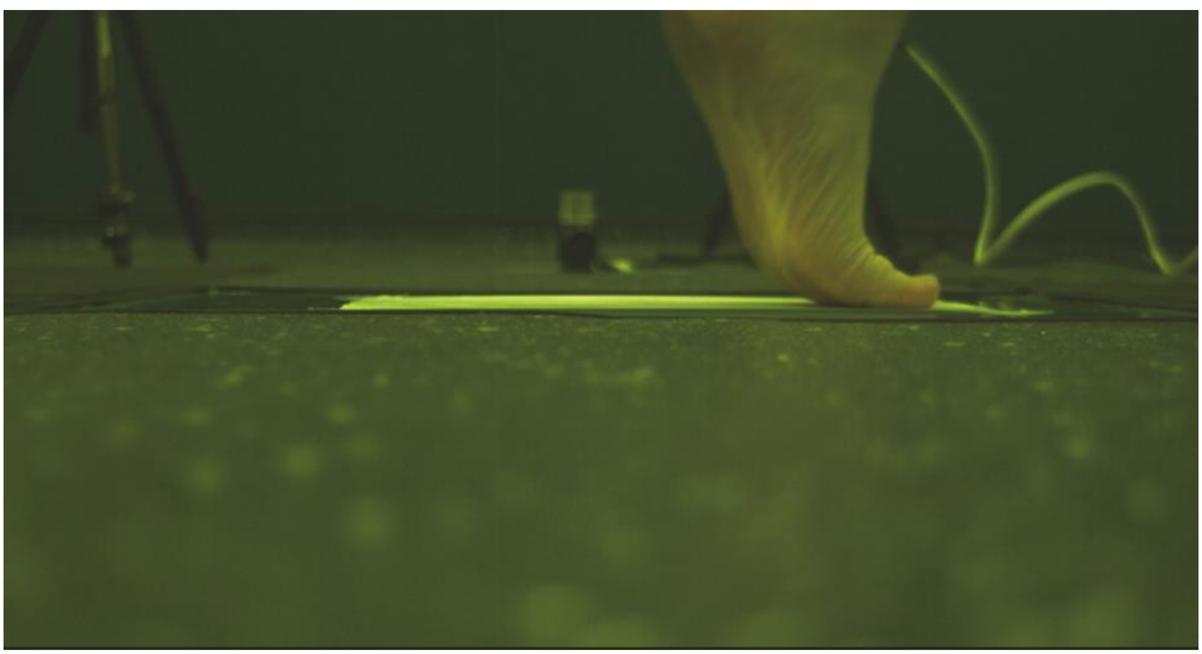


Fig. 7. Example of toe contact just prior to toe-off (Subject 11156515L)

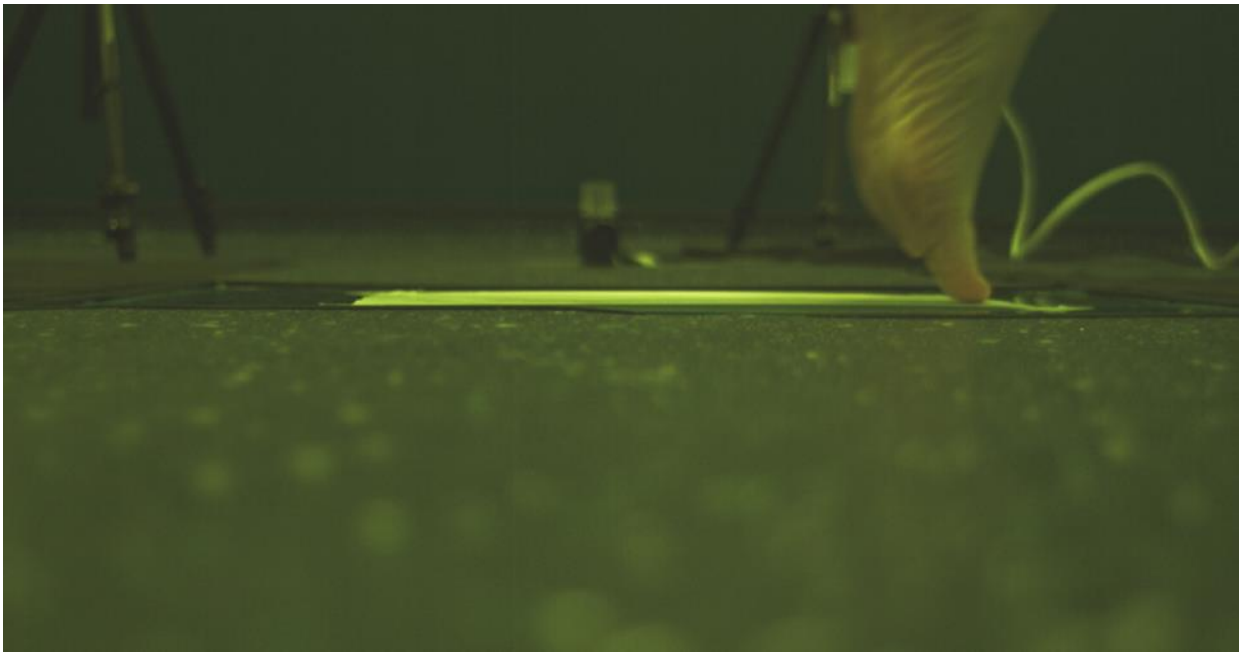


Fig. 8. Example of toe-off (Subject 11156515L)

3.3 Comparisons made

The visual recordings and ground reaction force graphs were used to establish the relationship between the ground reaction force and the position of the foot as the heel ghosting and inner dark areas of the bare footprints were being produced. At initial contact, the position of the heel related directly to the inner dark area of the heel for all footprints examined (Fig. 5). As the heel strike transient spike occurred in the vertical ground reaction force the fibro fatty pad of the heel began to compress and deform in all cases. The fibro fatty pads were clearly seen to splay out posteriorly to the heel. This briefly created heel to ground contact posterior to the position of initial contact (Fig. 6). At this point visual recordings appeared to show full body weight still being transferred to the ground via the main area of the heel (the area of the heel still corresponding with the inner dark area of that aspect of the footprint); not through the posterior splayed area of the fat pad. The posterior fibro fatty pad splay corresponded with the lighter ghosting features seen at the posterior heel area of the footprint.

The heel strike transient spike was observed in all cases, occurring immediately prior to the posterior splaying of the fibro fatty pad of the heel. The splaying continued to increase after the heel strike transient spike, as loading response continued (Fig. 4). This splaying of the fibro fatty pad resulted in a posterior increase in the area of the foot in contact with the ground.

Further comparisons between video recordings, vertical ground reaction-time graphs and the footprints showed the contact between the splayed fibro fatty pad (posterior to the heel) and the ground ended as the area of the foot in contact with the ground increased distally. Whilst the aspect of the heel that made initial contact was still in full contact with the ground, the vertical ground reaction force continued to increase. This area of the heel corresponded with the inner dark area of the heel in the associated footprints. The posteriorly splayed fat pad was therefore only in contact with the ground for a brief period of time and appeared to correspond with the outer ghosting areas of the heel prints.

At the forefoot, as the area of the foot in contact with the ground progressed distally, the toes were brought into contact with the ground along with the full length of the foot. At this point, for all participants, the most anterior aspect of the toes seen to be in contact with the ground appeared to correspond with the inner dark area of the toes of each bare footprint (Fig. 7). The vertical ground reaction force continued to increase, reaching a second peak force just prior to heel lift. In all cases, the inner dark area appeared to correspond with the area of the toes that had a greater duration of contact with the ground. This also corresponded with periods of higher vertical ground reaction force during the double support phase of gait (Fig. 4).

Towards the end of pre-swing, heel lift had taken place in all participants. As the loading was transferred to the opposite foot there was a period in which the apical aspects of the toes briefly contacted the ground (Fig. 8). During this period the vertical ground reaction force was seen to be rapidly decreasing prior to toe-off (Fig. 4). This period appeared to correspond in all cases with the formation of the outer ghosted areas seen in the bare footprints.

4. Discussion and conclusions

4.1. Discussion

Direct comparison of the video recordings, vertical ground reaction forces and bare footprints provided insight into the causative factors of the inner dark and outer ghosting features seen in dynamic bare footprints. The results of this work show that for the sample under consideration the inner dark area of the heel print may be formed as the main body of the heel initially contacts the ground and progresses through loading response as the vertical ground reaction force increases to the first main peak. It also became apparent that in the sample studied, the outer ghosting seen at the posterior area of the heel print was related to a rapid backward splaying of the heel fat pad. This followed the heel strike transient spike seen during heel loading. The contact between the splayed fibro fatty pad and the ground was of short duration. This suggests that the splaying fat pad may be aiding the dissipation of ground reaction forces in line with its known function “to accommodate friction and shock” [32]. The inner dark area seen in the toe prints appears to be formed in the period between first contact of the toes with the ground and the point at which the angulation of the toes relative to the ground begins to increase as the foot progresses towards toe-off. This primarily coincided with the second peak in vertical ground reaction force. The outer ghosting of the most anterior aspect of the toe prints appeared to occur during a brief period when only the apical aspects of the toes contacted the ground, occurring during the rapid reduction in vertical ground reaction force. Although the anterior/posterior ground reaction force was not studied in detail, the data did suggest that there was no dragging of the toes immediately prior to toe-off contributing to the outer ghosting, a finding supported by the video recordings.

The inner dark areas of dynamic prints could be seen as representing the true foot print which has been formed through the stance phase of gait, being formed during a prolonged period of contact of the foot with the ground, a period during which the majority of the vertical ground reaction force is exerted through the foot. The outer ghosting areas of the dynamic footprint appear to be formed during brief periods when either the splaying fibro fatty heel pad or the distal ends of the toes are in contact with the ground, periods when these areas of the foot appear to be subject to relatively lower vertical ground reaction force. In order to determine more exactly the timing of the formation of the various areas of the bare footprint a methodology would have to be developed that showed and recorded simultaneously the development of the footprint on the inkless paper, the movement of the foot and the ground reaction force, and is an area for further study. The results also suggest that further investigation is needed into the causative relationship between the formation of the inner dark areas and outer ghosting areas of the footprint, and the time the foot is in contact with the paper.

These observations are novel and while the study was small, this is the first reported work on the causes of these phenomena in bare footprints. The presence of a heel strike transient spike just after initial contact, as noted in this research, has been previously discussed in the literature and is known to be a regular occurrence [33]. However, the relationship of the features seen at the posterior heel print area, coupled with the associated heel strike transient spike has not been understood previously.

Despite these new appreciations, there are some limitations and areas where the work could be improved if repeated. While time based relationships between the various data sets were apparent, given the limited participant numbers for this study, it is uncertain whether these would apply every time such features are created. Similarly it could not be determined from these limited numbers whether there could be alternative causes of these features. As such, repetition of the work using much higher numbers of participants and involving other populations would be advantageous.

Another limitation relates to the need for participants' feet to land on a relatively small item (the sheet of inkless paper) during data capture. It is possible that in order to place successfully a foot onto this relatively small object, participants may have targeted the paper at the end of the swing phase as the relevant foot moved into stance, thereby potentially creating an initial contact at the heel strike that differed from the usual. However, studies investigating the effects of targeting on ground reaction force variability have shown no statistical differences between non-visually and visually-aided steps [34.35.36.37] and the five-step model has shown good repeatability.

Additionally, the work undertaken was not formal research but an observational action research project based in practice. While potentially open to criticism, two different forms of professional knowledge are known to exist

– theoretical and practical [38] with the latter being tacit knowledge gained by reflecting on experience [39]. What has been achieved in this study is an enhancement of the practical knowledge of the forensic podiatry profession. This work has achieved more than the simple understanding described by Polyani [40] as “that which practitioners know but cannot tell”, providing instead deeper understanding of foot function in the context of bare footprint formation. As such, the work can now lead to more formal, larger studies to develop further understanding in this area, in line with the purpose of this work.

The study has provided some evidence showing how the inner dark and outer ghosting areas are formed in dynamic bare footprints. It is now understood that within the limited sample studied, the features being considered are not anomalous, but instead relate to specific aspects of usual foot function. Particularly, the project has shown a link between the ghosting at the rear of the heel and the known heel strike transient spike typically occurring during heel loading [41] although further work on other populations would be useful.

In forensic podiatry practice there is now the potential to begin to extend the use of these features to give additional points for comparison as well as providing possible intelligence about what the subject was doing, i.e. whether they were moving or standing. However, although it is now known what these features are in the population studied, what is not yet known is how stable these features are within prints created by a single subject and what variation these features show between different subjects. As such, using this information in the forensic analysis of bare footprints should be set within the contextual limitations of the reported study.

Studies to compare the lengths of static prints with the length parameters of the inner dark areas of dynamic prints could now be undertaken to determine whether similarities are apparent between the two.

The results from this work suggest a possible cause for, and visible distinction between, the inner dark and outer ghosting areas of dynamic bare footprints. As most previously published barefoot print studies have not distinguished between these areas, caution should be applied if directly relying upon their findings.

4.2. Conclusions

This practice-based project was devised to investigate the causes of the inner dark and outer ghosting features of dynamic bare footprints through observation and comparison of different forms of data in a clinical laboratory situation.

The findings suggest that the ghosting at the heel is the result of splaying of the fibro fatty pad, while that at the toes is the result of the distal ends of the toes briefly coming into contact with the ground as the heel is lifted.

For the limited sample studied, the inner dark feature present at the posterior heel area of dynamic footprints appeared to correspond with the main body of the plantar heel surface that bears body weight during the first major vertical ground reaction force peak of the stance phase. The outer ghosting appeared to correspond with the limited ground contact created by a backward splaying of the heel fat pad.

For the toes, the inner dark area appeared to correspond with the longer period of time that the main body of the plantar aspect of the toes remained in ground contact, primarily during the second peak in vertical ground reaction force. The outer ghosting at the anterior aspect of the toes appeared to correspond with a brief period when the distal ends of the toes came into contact with the ground, occurring during a rapid reduction in vertical ground reaction force. These new appreciations open the way to the further development and use of these measurement landmarks in identification.

Unanswered questions remain regarding the stability of, and the level of identity shown by these features. Additional work is required with larger participant numbers, other populations and with participants walking at different speeds to confirm whether the findings apply within these different contexts. Further studies are also required to investigate the exact relationship between the formation of the footprint on the inkless paper and force and time, as well as whole body movement taking place as these features are being produced, to determine whether further insights can be elicited through this wider approach.

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