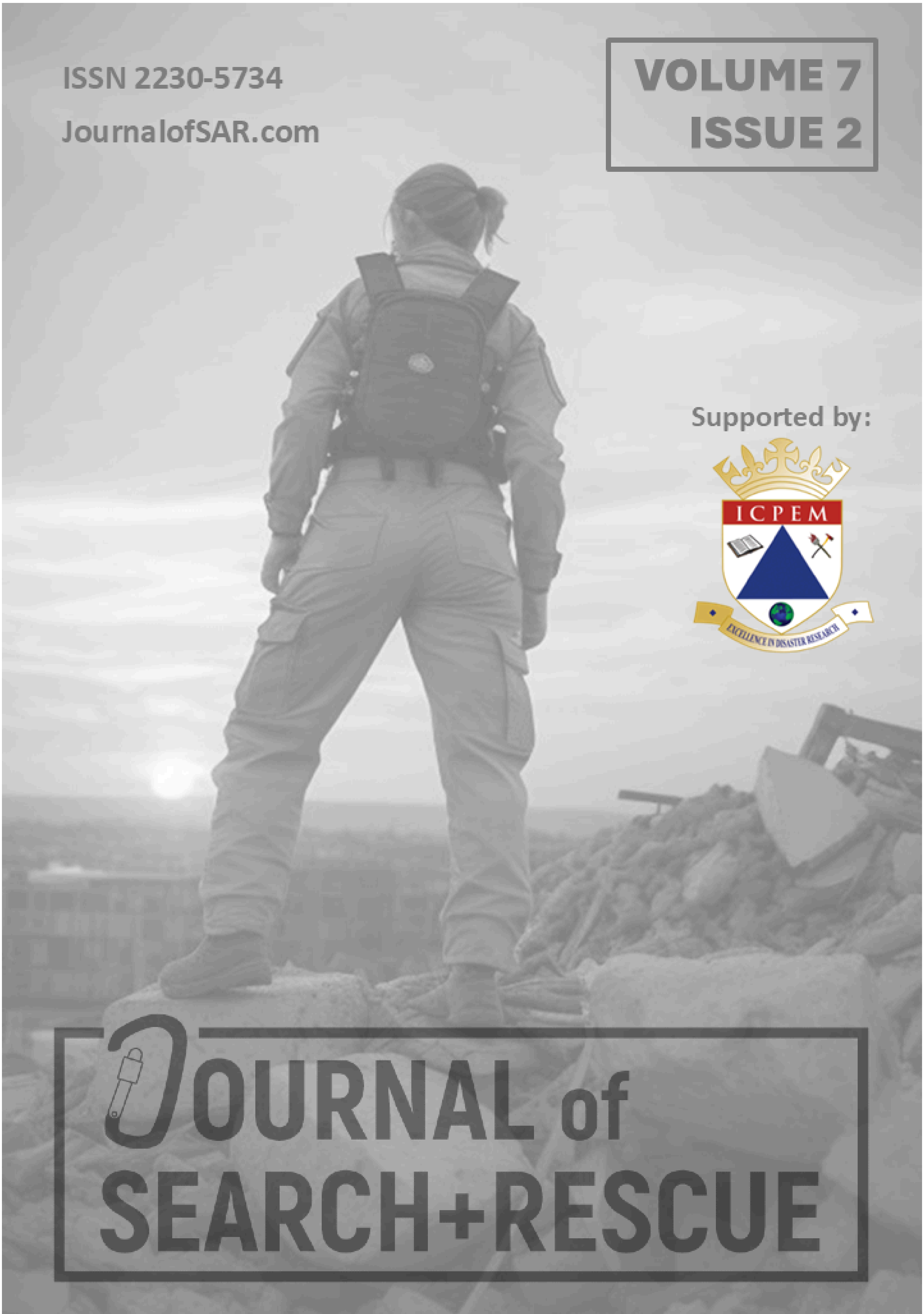

ISSN 2230-5734
JournalofSAR.com

VOLUME 7
ISSUE 2

Supported by:

ICPEM
EXCELLENCE IN DISASTER RESEARCH

JOURNAL of SEARCH+RESCUE

Volume 7, Issue 2, November 2024
Pages 124-213
ISSN 2230-5734

The Journal of Search and Rescue (JSAR) is an open access peer-reviewed electronic journal for the collation and distribution of original scholarly material on search and rescue (SAR).

It is being supported by the in-kind work and contributions of the Editorial Board. There is still the need for a dedicated journal serving those with a direct interest in all disciplines of search and rescue including: rope rescue, water (flat, swift and marine), ice rescue, wilderness search and rescue, structural collapse rescue, trench collapse rescue, cave rescue, dive rescue, motor vehicle extrication, canine search, technical animal rescue, air rescue, search theory, search management, and mines rescue. JSAR exists to fulfil that need.

Article submissions from these and other SAR disciplines are welcome. Launching this journal on the internet offers a relatively cost-effective means of sharing this invaluable content. It affords the prompt publication of articles and the dissemination of information to those with an interest in SAR.

JSAR will provide a forum for the publication of original research, reviews and commentaries which will consolidate and expand the theoretical and professional basis of the area. The Journal is interested in theoretical, strategic, tactical, operational and technical matters.

Advertising within JSAR will be considered in the future to ensure sustainable funding is available to enhance and continue the work of the journal. The publication of an article in the Journal of Search and Rescue does not necessarily imply that JSAR or its Editorial Board accepts or endorses the views or opinions expressed in it.

Editors: Toby Meredith, Dr Ian Greatbatch, Dr Scott Hammond & Dr Robert Koester
Editorial Team: Ian Allen, Chris Thompson, Ben Weedon
Journal manager: Linda Wyatt
Additional Materials Editor: Andy MacAuley

Editorial Board
Keith Gillespie ADFSc EMT-P
Steve Glassey MEmergMgt PGCPM GCTSS
Daniel Graham LLB (Hons)
Kay Goss MA CEM®

Andrea Kleinsmith, BS, MSc, PhD
Ian Manock MEmergMgt
Mike Rose MA MEPS
Brett C. Stofel BS JD

Volume 7, Issue 2, November 2024
Pages 124-213
ISSN 2230-5734

In partnership with

https://www.theicpem.org/

https://nasar.org/

www.isrid.net/

https://maritimesar.org/

https://www.landsar.org.nz/

Volume 7, Issue 2, November 2024
Pages 124-213
ISSN 2230-5734

Contents

Volume 7, Issue 2, November 2024
Pages 124-213
ISSN 2230-5734

Editorial

Welcome to Issue 2 of the 7th Volume of the Journal of Search and Rescue, the second in this volume and this year. We are immensely proud of the role of the journal, being freely accessible and providing peer reviewed research and contributions. The contributions cover a wide variety of issues pertinent to search and rescue, reflecting the diversity of search and rescue operations which are rarely out of the news.

As search and rescue professionals, we are acutely aware that time is critical during searches with a reliance on human searching alongside other resources and technologies. Searching of vast areas can present an array of challenges including communication, terrain and discerning relevant clues. Techniques to maximise best use of resource is essential and this edition presents two articles which can contribute to this discourse.

Our first is an article on a voice calling dedication algorithm. This presents an interesting tool that could be considered to maximise efficiency when searching and can be adopted with minimal requirements for additional resources. We also bring research that considers the impact that knowledge on the missing person's footwear may bring to a search. This could potentially further assist efficiency of a search with practical application. This author provides an invite opportunity to contribute data to further study.
The second part of our edition is a technical case study. This piece provides a comprehensive explanation on the use of wedge bolts including their use and considerations of the danger of misuse.

We finish this edition with a letter to the editor. This covers water rescue which is a skill undertaken within many search and rescue operations. Water presents its own challenges, and this letter discusses where there is potential for improving the effectiveness of water rescue operations.

We hope you find this issue useful and interesting; the journal will continue to publish robust research to develop the knowledge base in this area and welcomes submissions from authors.

Linda Wyatt,
Editor

Voice Calling Detection Distance in Land Search and Rescue

W. H. Finlay, PhD, PEng

Edmonton Regional Search and Rescue Association

Edmonton, Alberta, Canada

Email: warren.finlay@ualberta.ca

http://dx.doi.org/10.61618/SSOV3472

Abstract

The distance d_i at which shouts from a caller remain intelligible to a listener were measured in a wilderness coniferous forest and separately in an aspen parkland forest with the aid of members of the Edmonton Regional Search and Rescue Association. Values were determined for calling at an average sound intensity of approximately 88 dB at 1 m by both a male and a female caller. An equation based on existing models in the sound engineering literature was then developed that predicts this distance. This equation is given by $d_i = 5619 * e^{-0.0978\, dB_{amb}}$ where d_i is in meters and dB_{amb} is the ambient environmental sound level in dB at the listener's location, the latter measured using a smartphone with a sound decibel app. Although the spatial resolution of our d_i measurements is relatively low (measurement locations were 25-50 m apart in pine forest, and ≈ 5 m in poplar forest), and dB_{amb} fluctuated rapidly and considerably, giving considerable scatter to our data, predicted values agree with measured values of d_i, with a correlation coefficient of r^2=0.5. The equation captures the strong dependence of detection distance on ambient noise levels. This equation is an easily implemented tool requiring only a smartphone in the field. It allows prediction of voice detection distances when performing voice searching sweeps by SAR teams.

KEY WORDS: *voice detection range, acoustic search, calling, listening, shouting, speech intelligibility*

Introduction

A recent study (Costigan 2024) on the effectiveness of calling and listening during off-track ground searching for a lost person highlights the potential superiority of voice searching compared to visual searching for responsive subjects. The advantage of acoustic searching is its typically greater range of detection compared to searching by sight, although this depends on environmental conditions. Koester et al. (2013) found the average maximum detection range for searchers listening for shouting subjects was 322 m.

Auditory searching is of course useful only with responsive subjects, such as a lost hiker, angler, camper, gatherer, hunter, mountain biker, runner, or skier. Search areas for such subjects can be vast, as well as being difficult for off trail ground search travel. For example, 50% of lost hikers were found at distances greater 3.1 km from the initial planning point (Koester 2008). The considerably larger range of detection provided by auditory detection when doing sweeps of the search area can dramatically reduce search times for such subjects. However, auditory search requires two-way communication with the subject. Young children may not respond even if they are capable of doing so, while lost adults may be unable to respond if their physical condition has deteriorated. Thus, auditory searching is not suitable in some situations.

Whistles are commonly used in the search community to generate a signal during auditory searches, while the most common auditory response by subjects is shouting (Koester et al. 2013). Since whistles can typically produce a louder signal than shouting, they have a greater range of detection than shouting. This produces a mismatch where subjects may hear a searcher’s whistle, but searchers cannot hear the subject’s shouted response. Thus, if sweeping an area with multiple searchers proceeding along parallel lines, it is important to space searchers at a distance where they can hear shouts, not whistles.

It should be noted that the distance at which sound can be heard may be affected by a number of factors. Two of the most important such factors are the sound pressures (i.e. dB level) of the source sound and ambient noise. For example, a 6 dB change in either results in geometric attenuation halving the detection distance. Studies on sound attenuation in general also find secondary dependencies on sound frequency, ambient humidity, air temperature (ISO 1993), wind speed and topography (Kleiner 2012). Haupert et al. (2023) examined changes in sound attenuation of a white noise source between different forest habitats, finding it minor compared to geometric and atmospheric attenuation, although sound attenuation in forests can become considerable at higher frequencies (when trunk diameter is larger than the sound wavelength).

With so many factors possibly affecting the effective range of voice calling and listening, a logical approach to determining spacing between points where searchers call and listen would be for searchers to empirically determine the distance that shouts remain intelligible at each search. An analogous approach is frequently used to determine the visual range of detection and sweep widths in visual searching (Koester et al. 2014).

However, as noted above, the detection range for sound may be several hundred meters (Koester et al. 2013), and requires coordinating calling and listening by radio to determine detection range. This makes its measurement considerably more time consuming and involved than for visual range of detection. Despite this, efficient use and management of sound searching requires knowledge of sound detection sweep widths when spacing searchers in an auditory search, and for use in estimating probability of detection (POD) of sound sweeps.

Given the above, it would be useful if a simple model was available to predict distances over which searcher's calls can be heard. As noted by Bowditch et al. (2018), if multiple searchers are calling, it is important for callers to be intelligible in order that listeners can distinguish a responding lost person from the calls of other searchers. Thus, it is the distance d_i between a caller and listener over which speech remains intelligible that would be most useful for such a model to predict. Predictions of d_i for short distances were first made for male voices with application to speech communication inside aircraft shortly after World War II, and later modified (Weber 1973) and subsequently compared to experiments that included female voice (Waltzman and Levitt 1978). Standard curves of d_i (see e.g. Foreman 1990) for different levels of vocal effort (normal voice, raised voice, very loud, shout, maximum vocal effort) plotted as a function of Speech Interference Level (SIL), which is the average ambient sound level in dB measured at a number of different frequencies, were subsequently adopted by the sound engineering community to aid in design of human communication spaces, such as conference rooms and work spaces. In the present work, we measure d_i between search and rescue (SAR) searchers in two outdoor wilderness settings consisting of either pine or poplar forest. We also develop a simple model to predict d_i based on the existing literature noted above. The ability of this model to predict our measured values of d_i is then examined.

Methodology

Experimental Methods

Members of Edmonton Regional Search and Rescue Association (ERSARA) were recruited to volunteer in voice detection range experiments. Experiments were performed in a coniferous forest, composed of mature, dense lodgepole pine (trunk diameters of approximately 0.2 m) located in remote wilderness in western Alberta, Canada in a relatively flat area (all listening locations were within 13 m of elevation of each other) in the Wildhay River valley within the Rocky Mountain foothills near 53.50382^0 N 118.01143^0 W. Figure 1 shows a satellite image of the location. Experiments were performed the afternoon of June 8, 2024. At the start of the experiments, measured ambient temperature was 8^0 C, relative humidity was 48%, atmospheric pressure was 86.6 kPa and ground wind speed was 4-6 km/hr from the west. Data acquisition was completed within 2.5 hours, over which time ambient weather conditions did not change measurably.

Sound pressure levels (in dB with 20 mPa reference sound pressure) were measured using the participants' smartphone pressure transducers with either Sound Meter (Splend Apps) or Sound Meter Decibel (Sweetvrn), which are free smartphone apps. No calibration of the smartphone measured dB values was done.

Figure 1. Satellite image captured on Oct 15, 2015 of the location of the sound detection experiments in coniferous forest. The calling location is marked by the white star. Searchers listened at points located on the white line. The three grey lines show schematic examples of straight line sound ray paths from the caller to the listeners through the forest. Copyright free satellite image courtesy of Environmental Systems Research Institute.

One volunteer remained as a caller at the calling location. The remaining searchers traveled away from the caller and then stopped to listen at points in time, coordinated by radio communication. The caller could not be heard at the initial listening point. Radio contact was made with the callers at each location and the straight line distance and bearing to the caller was recorded by each caller. The caller and listeners then faced directly toward each other on this bearing. The caller then confirmed via radio that the listeners were ready, and the caller then proceeded to shout three words, which were different each time and chosen randomly from the names of Canadian provinces and US states. Each time the caller shouted, the peak dB value of the set of three words was recorded using a smartphone directly facing the caller on a tripod at a measured distance of 1 m. Each listener individually recorded what words they understood, as well as the environmental ambient dB level (dB_{amb}) at that approximate time and their location. Incremental distances between the listening locations varied, but were approximately 25 m for locations within 100 m, and 50 m for distances > 100 m from the caller.

One set of measurements was performed with a male caller shouting to three male listeners and one female listener. Another set of measurements was performed with a female caller with the same three male listeners. The volunteers ranged in age from 30-62, with median age 43.

To explore the effect of caller/listener orientation, one set of measurements was also performed with the male caller facing directly away from the listeners, and the four listeners facing directly away from the caller. As usual, the caller recorded the peak dB value of the set of three words with their smartphone directly facing them on a tripod at a measured distance of 1 m.

To further examine the effect of facing away from the listeners, three measurements of the peak dB value of the male caller were obtained with the smartphone placed 1 m directly behind the caller.

For each listener, the distance d_i at which the caller was considered intelligible was determined as being halfway between adjacent locations where two words were correctly understood at the closer location and one word was correctly understood at the further location. This corresponds to approximately 50% speech intelligibility. The caller could be heard at much larger distances than d_i, but words could not be understood at those distances.

In a final set of measurements in the coniferous forest habitat, the male caller instead played bagpipes and the above three male listeners recorded the maximum distance at which the bagpipes could be heard when facing the listeners. The dB level at a distance 1 m in front of the bagpipes was recorded.

To explore the effect of vegetation habitat on d_i, we collected a smaller set of data in a deciduous aspen parkland forest (trunk diameter of approximately 0.2 m). This data was obtained on Aug. 18, 2024 within the Cooking Lake-Blackfoot Provincial Recreation Area near 53.47162^0 N 112.89556^0 W, a 97 km^2 forested area east of Edmonton, Alberta, Canada. Volunteers from ERSARA were again recruited. One female listener and two male listeners, median age 41, participated. These were different individuals than in the coniferous forest experiment. The same male caller was used as in the coniferous forest experiment. Ambient temperature at the start of data acquisition was 21^0 C, ambient pressure was 92.98 kPa, relative humidity was 46.6% and winds were 0-5 km/hr from the west. Data acquisition was completed within 2.5 hours, over which time ambient weather conditions did not change measurably. Unfortunately, one listener's smartphone recorded dB levels approximately 20 dB less than the other three participant's smartphones; it was assumed that the pressure transducer on that smartphone was faulty, so values of the other nearby participants' measurements of ambient dB levels were used instead when predicting d_i for this listener. The model described below was used in the deciduous forest experiment to predict listener starting locations. This saved time and allowed us to achieve finer spatial resolution in the deciduous forest, with listening locations approximately 5 m apart on either side of the critical spacing in this habitat. The initial listening location was at a distance of approximately 200 m, at which distance no words were intelligible to any of the listeners. The forest at the caller's location facing the listeners is shown in Figure 2. Similar forest habitat occurred over the entire straight line distance between the callers and listeners i.e. there were no intervening meadows, water bodies or open areas. All listening locations were within 3 m of elevation of each other.

Figure 2. The view of at the deciduous forest calling location, looking toward the listeners.

The Model

While more recently developed models of speech intelligibility than those noted in the Introduction are typically used by sound engineers and audiologists today, these more sophisticated models are more complex and require specialized audio spectral measurement and analysis equipment. To maximize the possible adoption of a model by civilian SAR agencies, minimizing analysis and specialized equipment was prioritized. For this reason, we chose to work from the Speech Interference Level (SIL) curves noted earlier (Foreman 1990). These curves plot the distance d_i at which speech is intelligible for different vocal efforts as a function of measured SIL. However, determining SIL requires averaging the values of ambient noise dB levels at a number of specific frequencies, which requires acoustic equipment that is unlikely to be available to SAR personnel. Instead, here we replaced SIL in these curves with the average ambient environmental sound dB value measured by the smartphone decibel measuring apps noted earlier.

For vocal effort in the published SIL curves, we chose to interpolate a curve halfway between the curve for shouting and the curve for maximal vocal effort. The standard SIL curves assume geometric attenuation of sound (i.e. sound intensity decreases as $1/r^2$ where r is distance from the sound source), which implies a 6 dB attenuation for every doubling of r, whereas Kleiner (2012) notes that atmospheric turbulence and excess absorption (due to heat conduction, viscous losses and relaxation phenomena) results in slightly higher measured total attenuation values near 7 dB. Thus, here we create a curve that interpolates SIL values of 107.5 dB at 0.15 m and 65 dB at 9.8 m, which gives 7 dB attenuation for each distance doubling and is expected to approximate typical intelligibility distance for a loud shout including geometric and atmospheric attenuation.

The resulting model for distance d_i at which a shouting individual is expected to be intelligible enough for SAR purposes can then be found to be given by

$$d_i = 5619e^{-0.0978\, dB_{amb}} \quad (1)$$

where d_i is in meters, and dB_{amb} is the ambient sound level as measured with a smartphone sound decibel app.

Since not all SAR field personnel may be comfortable using the exponential function, eqn. (1) can equivalently be written as

$$d_i = 5619 * 10^{-0.04247\, dB_{amb}} \qquad (2)$$

Eqns. (1) and (2) assume the caller exerts a vocal effort midway between a shout and maximum vocal effort i.e. a loud shout, which corresponds to an SIL of 88 dB at 1 m. Callers shouting with lower dB than 88 dB at 1 m can be modeled by replacing dB_{amb} with dB_{amb}+(88-$dB_{\_caller}$) in these equations i.e.

$$d_i = 5619e^{-0.0978\,(dB_{amb}+88-dB_{caller})} \qquad (3)$$

Note that it can be shown that eqns. (1) and (2) imply that sound intensity attenuates with distance r from the sound source as $1/r^{2.35}$, rather than $1/r^2$ as occurs for purely geometric attenuation.

Results

Figure 3 shows predicted values of the distance that loud shouts are intelligible as a function of ambient dB, calculated using eqn. (1) or equivalently eqn. (2).

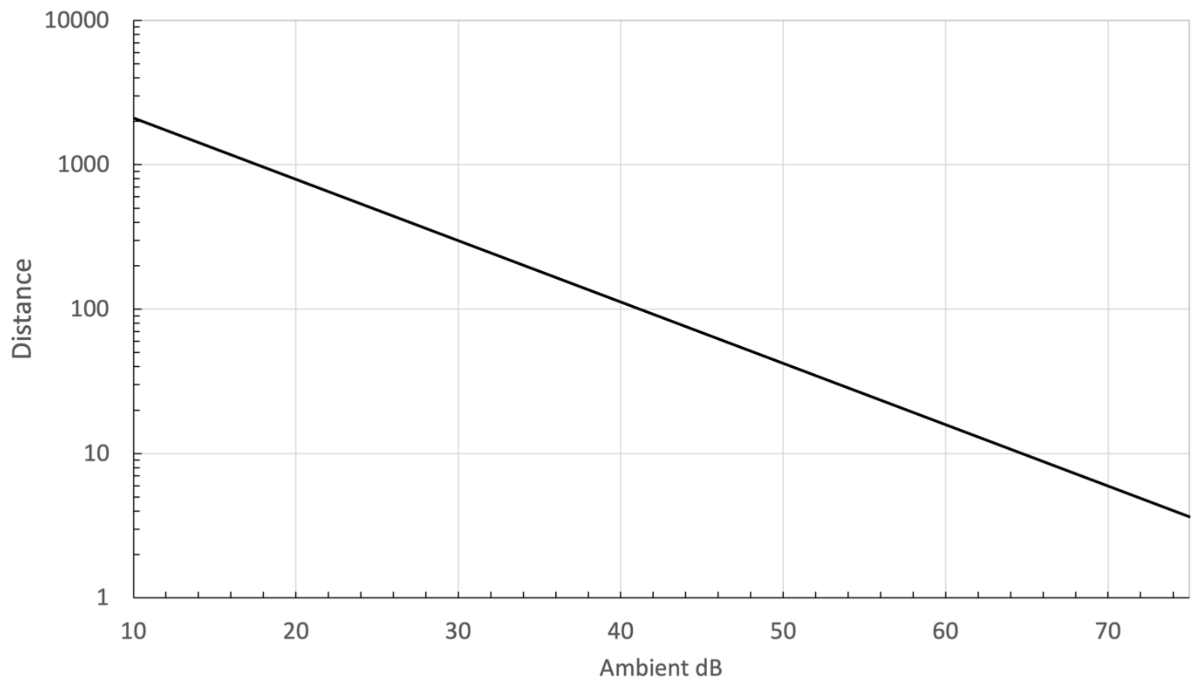

Figure 3. The distance d_i (in meters) that loud shouts are predicted to be intelligible are shown as a function of ambient noise levels (in dB).

In our field experiments in coniferous forest, the peak dB levels measured at 1 m for the male caller shouts varied from 84-95 dB, while those of the female caller varied from 82-92 dB. The value of the caller's peak dB measured at 1 m for the two locations that sandwiched d_i when facing toward the caller was 87 dB for the male caller, and 89.5 dB for the female caller, while the average for both callers was 88 dB ± 1 dB (mean±s.d., n=7). The average peak dB of both male and female callers overall was 88.8 dB±4 dB (mean±s.d., n=21) at 1 m. The average value of the caller's peak dB at the two locations that sandwiched d_i when the caller and listeners were facing directly away was 88±1 dB (mean±s.d., n=4) at 1 m. The average reduction in peak dB of shouts measured 1 m directly behind the caller versus directly in front of the caller was 7±1 dB (mean±s.d., n=3). Ambient noise levels measured at each listening location by each listener varied from 25-60 dB, with a mean value of 43 dB ± 10 dB (mean±s.d., n=64), sometimes varying over nearly the entire range between one listening time and the next, due to wind gusts. Beyond a distance of approximately 200 m in the coniferous forest, listeners were unable to hear the caller; ambient noise levels ranged from 45-60 dB when listeners were at those distances.

In the deciduous forest, the average peak dB level at 1 m from the caller was 89±3 (mean ± s.d., n=21) and varied from 86-95 dB. Ambient dB levels ranged from 32-52 dB with a mean value of 40±7 dB (mean±s.d.,n=21). The two male listeners were unable to hear the caller at all beyond distances of approximately 270 m, while the female listener could not make out any sound from the caller beyond approximately 329 m. Ambient noise levels ranged from 32-40 dB when listeners were at those distances.

Figure 4 shows predicted values from eqn. (1) versus measured values of the distance d_i for both forest habitats. The Pearson correlation coefficient is r^2=0.5 when facing toward the caller (the case for which eqn. 1 it was designed). For the case of the male caller facing away from the listeners (who were also facing away from the caller), we have used eqn. (3) with 88-dB_{caller}=7 dB.

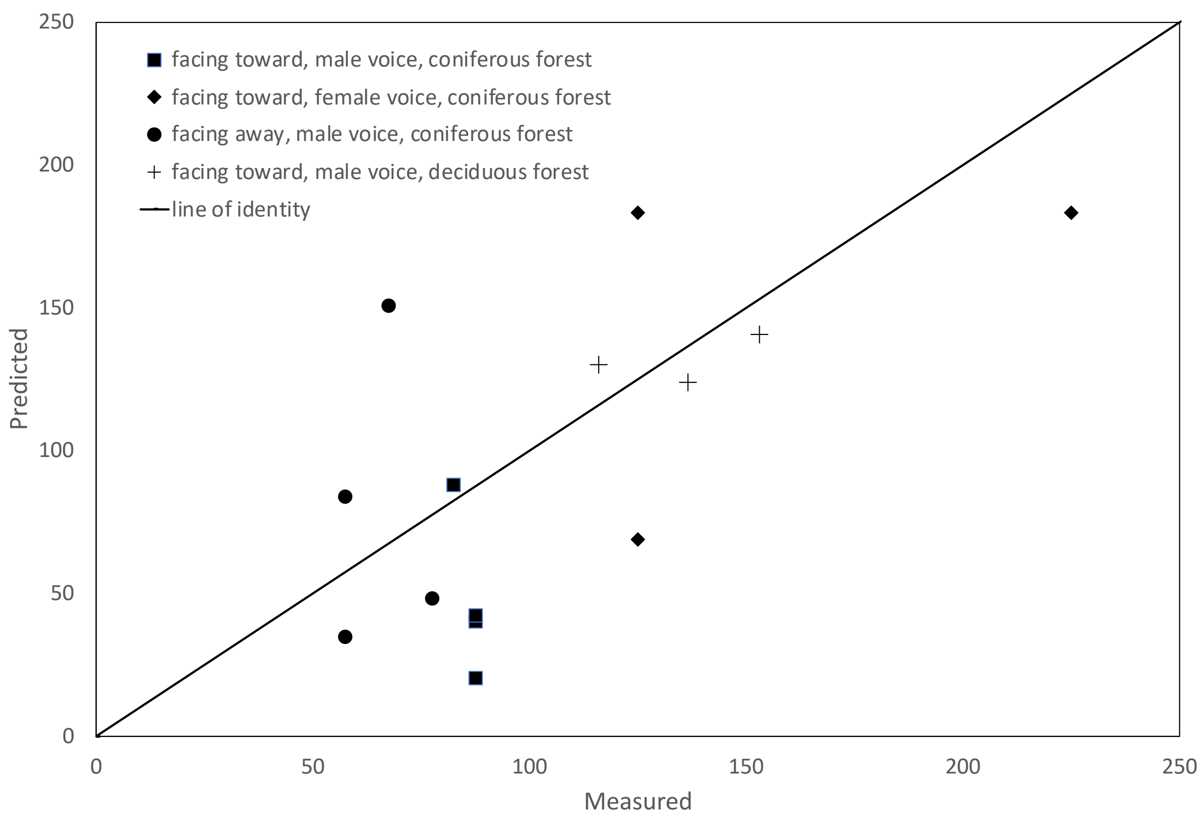

Figure 4. Predicted values of the distance d_i at which the caller is intelligible are shown versus measured values for a male caller and a female caller facing the listeners, as well as for a male caller with both caller and listeners facing away from each other, all in a coniferous forest. The three data points obtained in deciduous with only a male voice calling are also shown. The line of identity (where predicted and measured values would be equal) is shown for reference.

The measured peak sound intensity of bagpipes at a distance of 1 m was measured to be 97.3 dB±2.5 dB (mean ±s.d., n=3) and could be heard out to a distance of approximately 450 m in the coniferous forest.

Discussion

Considering that the model given by eqn. (1) was developed *a priori* without any adjustable or fitted parameters, it is surprisingly predictive of the measured data, with an r^2 value of 0.5 when considering all data facing toward the caller in both forest habitats. The scatter seen in Figure 4 is unsurprising given the low resolution of many of our measured d_i values, probable interdevice smartphone variability in measured values of dB levels (Murphy and King 2016), as well as the high variability and rapid changes in ambient noise levels when listening. The latter made it difficult to specify a reliable single value of ambient noise (dB_{amb}) at the listening time/location; the sensitivity of d_i seen in Figure 3 to dB_{amb} amplifies uncertainty here and adds to the scatter seen in Figure 4.

The average magnitude of the difference between predicted and measured values of intelligible shouting distance was 29 m± 20 m (mean±s.d., n=7) when facing toward the caller in the pine forest, which is 25% of the average d_i. This is similar to the spacing between listening locations, and this accuracy may be all that can be expected from a model when comparing to our low resolution experimental data. For the deciduous forest data, the average magnitude in the difference between predicted and measured d_i values was 13 ± 1 m (mean±s.d., n=3), which is 10% of the average d_i. The smaller difference between predicted and measured values in the deciduous forest is presumably due to the closer spacing between listening locations in the deciduous forest data (approximately 5 m), which itself was the result of using equation (1) to predict starting locations for the listeners, allowing time to achieve better spatial resolution in the deciduous forest.

Some variability in our data may be due to differences in measured dB values by our uncalibrated smartphones. Previous studies have shown that different smartphones and noise measurement apps give different measurement values for the same noise source (Murphy and King 2016). Most of our measurements were made using the Sound Meter app, which Murphy and King (2016) found gave an average error of 2 dB with a standard deviation of 9 dB among 140 individual smartphones. Thus, either calibrating smartphone dB values against a dedicated dB meter, or at least using the average of multiple smartphones for measuring dB measurements, would be useful in future studies or application of the present work.

The SIL curves upon which the present model was developed were based on data with subjects facing toward each other at short distances (< 16 m) in inside settings. Despite extrapolating these curves to much larger distances here and to an outdoor forest setting, we find eqn. (1) remains predictive. In retrospect, the lack of attenuation by intervening forest habitat is not surprising, since Haupert et al. (2018) found attenuation due to forested habitat is minor. In their experiments, they measured attenuation out to 100 m away from a 78 dB or 83 dB (measured at 1 m) white noise sound source in a coniferous forest and a neotropical rainforest, finding an average attenuation of 0.02 dB/kHz/m. The overall average d_i measured here was 98 m in coniferous forest (and 135 m in deciduous forest), and assuming a voice frequency of 0.5 kHz, the data of Haupert et al. (2018) would imply approximately 1 dB of attenuation over this distance due to the presence of forest, although this attenuation is linearly proportional to frequency (Haupert et al. 2018). This is negligible compared to the 40 dB geometric attenuation and 7 dB atmospheric attenuation predicted over a distance of 98 m by the 7 dB per distance doubling associated with the model given by eqn. (1). The presence of forest vegetation on voice detection distances in SAR thus appears not to meaningfully affect the ability of eqn. (1) to predict these distances. This is supported by the ability of equation (1) to also independently predict the limited data we obtained in aspen parkland, although it may be worthwhile to obtain data in still other habitats and ambient meteorological conditions.

Extending eqn. (1) to callers and listeners facing directly away from each other by using a measured 7 dB reduction in shout volume (due to vocal directivity shadowing by the caller's head) in eqn. (3) reduced the overall r^2 value to 0.4. Note that differences in pinna response between facing directly toward and directly away have been previously found to be small (Kleiner 2012), so the difference observed here is presumably due to voice directivity, rather than listening directivity. While the number of datapoints here is small and are scattered (10 values of d_i facing toward and 4 values facing away), this reduction in r^2 might be due to unaccounted for differences in voice directivity when callers and listeners are at angles other than facing toward each other. Indeed, differences in voice directivity due to shadowing of the head are quite frequency dependent, and with speech intelligibility dependent more on higher frequencies (Kleiner, 2012), it may be that using a single caller dB attenuation to account for voice directions other than face on is too simplistic. Despite this, the clear reduction in detection distance we observe when facing away from the listener indicates that voice searchers should call facing multiple directions at each calling location to mitigate voice directivity e.g. searchers should call in both directions perpendicular to the search path, as well as forward and backward along the search path.

The eight callers in the SAR study by Bowditch et al. (2018) shouted at 75±2 dB measured at 5 m. This corresponds to 89 dB at 1 m assuming purely geometric attenuation. This is the same value of average loudness as the two callers we measured here. Thus, the dB of calling used here to validate eqn. (1) may be considered within the range of typical values of loud shouts. Searchers may consider calibrating their shout loudness using a smartphone decibel app at a distance of 1 m to achieve an approximate 88 dB average shout sound intensity when using eqn. (1) to estimate detection distances. An alternative to calibrating call intensity would be to measure calling dB levels and then use eqn. (3).

The use of bagpipes allowed us to examine detection distances of a louder sound. With an assumed 7 dB attenuation per distance doubling, the average 8.5 dB increase in sound intensity of the bagpipes compared to shouting here implies detection distances should be 2.3 times larger for bagpipes than shouting. Since speech intelligibility is irrelevant for detecting bagpipes, comparison between voice and bagpipe detection distances needs to done based simply on the distance at which the caller shout is heard (but is unintelligible). We did indeed find bagpipes could be heard approximately 2.3 times further away than shouting. Given that it is difficult and potentially hazardous to the vocal cords to maintain a voice level > 85 dB for extended periods (Waltzman and Levitt 1978), bagpipes may be a useful tool worth considering to attract response over an extended period of time of a lost subject that may be within bagpipe detection range of the last known point. While whistles are commonly used to generate a signal by SAR searchers, they may not be as loud as bagpipes (two whistles we measured gave signals of 90 and 95 dB loudness at 1 m). In addition, the possibility of providing longer duration sound with bagpipes that is not associated with distress, like whistles are, may be advantageous in garnering a response from certain subjects e.g. children. Because of the much greater detection range of the bagpipes, the use of a parabolic mic for listening at the last known point would be useful, which Bowditch et al. (2018) find extends the range of detection by a factor that is similar to the 2.3 times factor that we see here for bagpipes vs voice range of detection.

Eqn. (1) (or equivalently eqn. 2) may be useful in estimating the distance between calling-listening locations and critical spacing when executing voice searches. A simple measurement of ambient sound levels on a smartphone decibel app allows eqn. (1) to directly predict the voice detection range. Assuming the sound from the caller propagates hemispherically above flat ground (which neglects the previously noted voice directivity effects), the range of detection is then a circle centered on the caller's location. If no response is detected at that location, then if the search team proceeds a distance 2*di from that location to call again, the range of detection circles from the two locations would just touch, as seen in Figure 5. If the distance between calling locations is a straight line along a search path, there is then an area that is beyond the detection range but still within d_i of the search path, shown as the shaded region in Figure 5. This area is easily calculated by numerical integration. From a probability of detection (POD) perspective, it can then be shown that sweeping along a search path with calling/listening locations separated by a distance of $2d_i$ results in voice coverage of c=78.5% of the area within d_i on either side of the path. Moving the calling-listening locations closer yields c=89.6% and c=95.7% coverage for separations of $1.5d_i$ and d_i respectively. If searching an area, then as a first approximation, POD can be estimated by simply multiplying the searched path length by $f=0.02\ c\ d_i$ (i.e. $(c/100)*2*d_i$) and dividing by the search sector area. For calling-listening points separated by $2*d_i$, $f=1.57\ d_i$.

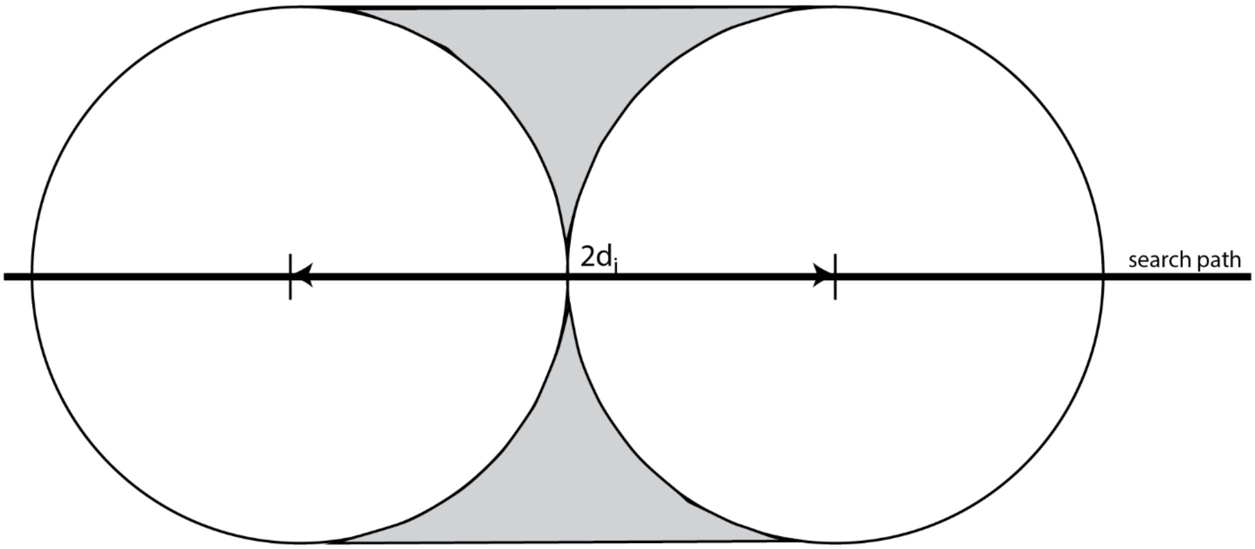

Figure 5. Schematic drawing of the intelligible detection area that results when calling and listening occurs at two points separated by two times the detection range d_i along a search path. The shaded area is outside the intelligible detection range and can be shown to leave 21.5% of the area within d_i of the search path beyond the intelligible detection range.

A subject in the shaded region in Figure 5 is beyond the intelligible speech detection range, so intelligible voice communication between the searchers and subject is not possible. However, given the much larger range that we find shouts remain detected but unintelligible, searchers would presumably move closer to the subject if they hear a response, albeit at an unintelligible distance, to establish intelligible vocal communication and result in a successful search. Regardless, the above noted POD estimate may be useful as an approximate measure for use in search management.

Operationally, auditory sweeps that use shouts for signaling are probably best limited to higher probability areas, since searchers are likely to find it difficult to shout at loud levels throughout an entire operational period. A typical operational application of eqn. (1) would be for a sound sweep of e.g. a 600 m x 600 m square centered on the last known point. In this case, measurement of ambient environmental sound levels, preferably averaging values from several smartphones or using a smartphone whose measured dB values have been calibrated against a dedicated dB meter, provides a value of dB_{amb} to use in eqn. (1) to predict a value of the distance d_i at which shouts are heard with approximately 50% intelligibility. A set of parallel lines at a chosen bearing and separated by a distance of $2d_i$ should then be decided upon that most efficiently traverses the search area. Individual searchers would then position themselves on these individual parallel lines separated by a distance of $2d_i$, stopping at locations every $2d_i$ to shout forward, backward, and perpendicular to each side of the line they are following. For example, if d_i=100 m, then a 600m x 600m square would be swept by three searchers spaced 200 m apart and stopping 100 m, 300 m and 500 m from one side of the square, each having walked 500 m along parallel lines and shouted 12 times (once in each of 4 perpendicular directions at three locations along their sweep line). Figure 6 shows a schematic representation of the above operational implementation of this with d_i=100 m and three searchers. With a different value of d_i, replacing the 100 m distances with d_i in Figure 6 and the 200 m distances shown in Figure 6 with $2d_i$ would result in the same operational procedure sweeping a square with side $6d_i$.

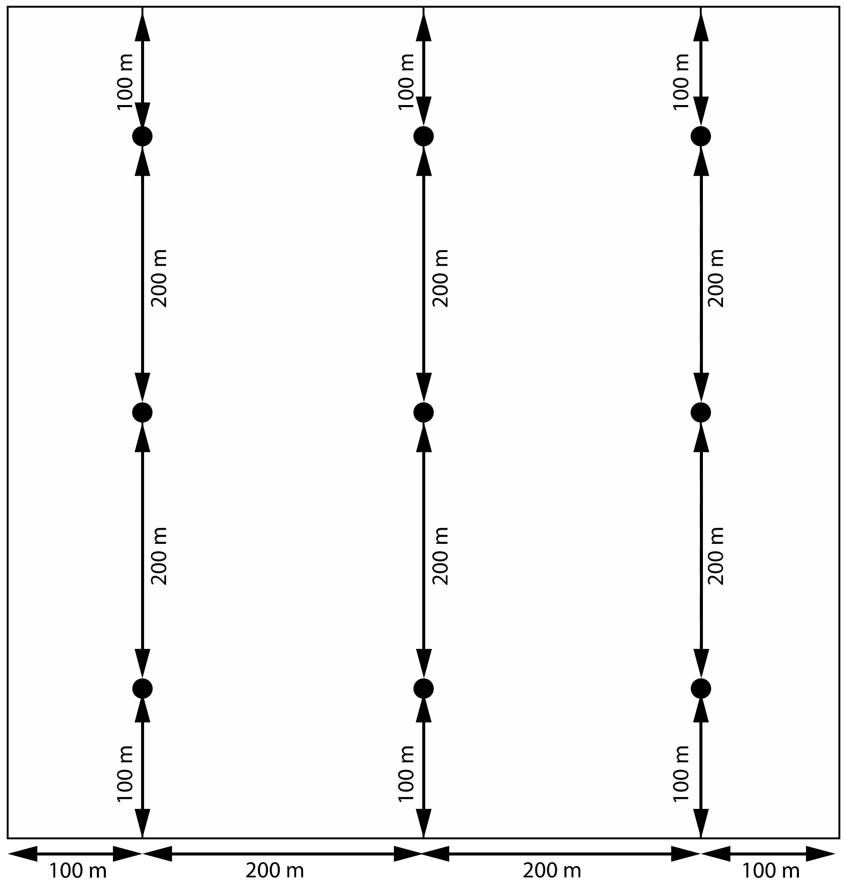

Figure 6. Schematic of auditory sweep distances for a detection range d_i=100 m with three searchers following parallel lines to search a 600m x 600m square shown by the solid line boundary. Calling locations, where searchers stop to shout and listen in four different directions (forward, backward and to each side), are indicated by the solid circles.

Searchers may want to agree on what words they are shouting e.g. if the subject's name is Jane, then perhaps 'Hello Jane; calling Jane; are you there Jane'. In this example, there would be no need to coordinate the timing of searcher calls since each searcher would be intelligible to each neighboring searcher (since they are separated by a distance of d_i) and distinguishable from the subject's response. The distance between searchers could be modified during the search if neighboring searchers are unable to make out any words that adjacent searchers are shouting, or if every word is very clear and intelligible. This would empirically optimize searcher spacing to accommodate varying searcher shouting and hearing levels, as well as temporally varying ambient noise levels. Once the searchers have traversed the width of the search area, the above noted procedure for estimating POD can be used.

Limitations of this study

The effect of local topography, such as hills or cliffs, on sound propagation is not included here; neither are the effects of temperature and wind speed variations with height, which can bend sound ray paths to create sound shadows and result in d_i being different from that predicted and measured here. We did not clinically assess the hearing abilities of the participants. However, none of the participants in our field measurements had a diagnosis of hearing loss, so the effects of hearing loss are not included. Eqn. (1) does not account for differences in atmospheric losses at different relative humidity, temperature or atmospheric pressure. Standard equations are available for this purpose (ISO 1993), which predict atmospheric losses that vary from 0.01-8.5 dB over a 100 m distance for frequencies varying from 100-3150 Hz, humidities from 10%-100%, and temperatures from -20^0 C-+30^0 C at 101 kPa atmospheric pressure. These are small compared to the 40 dB of geometric attenuation over this distance. Given that these losses are minor compared to geometric attenuation, as well as being strongly frequency dependent, our inclusion of them as a 7 dB loss over a 100 m distance may be of sufficient accuracy for the intended SAR applications of our model.

Conclusions

We present a simple equation given by $d_i = 5619e^{-0.0978\, dB_{amb}}$ that requires only the measurement of ambient environmental noise levels dB_{amb} using a smartphone to then predict the distance d_i over which a shouting person remains intelligible when shouting at a typical loud shout sound intensity of 88 dB (measured at 1 m). We then compare the predictions of this equation to measurements we have made of d_i in a coniferous forest wilderness and in a deciduous forest. Despite the relatively low spatial resolution of our field measurements (listening distances were separated by 25-50 m in the coniferous forest and approximately 5 m in the deciduous forest) and highly variable ambient noise levels (due to wind gusts), this equation is predictive of the measured values (r^2=0.5). Forest habitat attenuation is expected to be negligible compared to the much greater geometric and atmospheric attenuation that are captured by this equation. Thus, the present model may be useful for SAR teams wanting to predict voice searching detection distances in general.

Acknowledgements

The assistance of Edmonton Regional Search and Rescue Association (ERSARA) and in particular ERSARA members Peter Bezeau, Michael Cooley, Danielle Everitt, Ethan Mason, Kyle Schole, Nancy St. Hilaire, and Richard Willimus, who participated as field subjects in this study, is gratefully acknowledged.

About the Author

Warren Finlay is a Search Manager with Edmonton Regional Search and Rescue Association. He holds a PhD in Mechanical Engineering, is a Registered Professional Engineer, and has published more than two hundred refereed archival journal papers in aerosol mechanics and fluid dynamics during his tenure as a Professor at the University of Alberta. He is a Fellow of the Royal Society of Canada.

References

Bowditch, N. L., Searing, K. S., Thomas, J. A., Thompson, P. K., Tubis, J. N., Bowditch, S. P. (2018) "Use of a Parabolic Microphone to Detect Hidden Subjects in Search and Rescue", Wilderness and Environmental Medicine 29:11-17.

Costigan, R. (2024) "The Value of Searching by Voice in LandSAR", J. Search and Rescue 7 (1):1-29.

Haupert, S., Sebe, F., Sueur, J. (2023) "Physics-based model to predict the acoustic detection distance of terrestrial autonomous recording units over the diel cycle and across seasons: Insights from an Alpine and a Neotropical forext", Methods Ecol. Evol. 14:614-630.

ISO International standard "Acoustics - Attenuation of sound during propagation outdoors - Part 1", ISO 9613-1:1993(E).

Foreman, J. E. K. (1990) *Sound Analysis and Speech Control*, Van Nostrand Reinhold, NY, NY.

Kleiner, M. (2012) *Acoustics and Audio Technology*, 3rd Edition, J. Ross Publishing, Ft. Lauderdale, Florida.

Koester, R. J. (2008). *Lost Person Behavior*, dbS Productions LLC, Charlottesville, Virginia.

Koester, R. J., Gordon, R., Wells, T., Tucker, R. (2013) ‘Auditory and light based two-way effective sweep width for responsive search subjects in New Zealand mountainous terrain’, J. Search and Rescue 1:1-18.

Koester, R. J., Chiacchia, K. B., Twardy, C. R., Cooper, D. C., Frost, J. R., Robe, R. Q. (2014) “Use of the Visual Range of Detection to Estimate Effective Sweep Width for Land Search and Rescue Basedon 10 Detection Experiments in North America”, Wilderness and Environmental Medicine 25:132-142.

Murphy, E. and King, E. (2016) “Testing the accuracy of smartphones and sound level meter applications for measuring environmental noise”, Applied Acoustics 106:16-22.

Waltzman, S. B. and Levitt, H. (1978) “Speech Interference Level as a Predictor of Face-face Communication in Noise”, J. Acoust. Soc. America 63:581-590.

Webster, J. C. (1973) “The effects of noise on the hearing of speech”, in *Proc. Internation. Cong. Noise as a Public Health Problem*, Dubrownik, Yugoslavia, pp. 25-57, US EPA, Washington.

Optimization of a handheld line launcher for microgravity utility and rescue tasks

John LaRocco, PhD
Ronin Institute for Independent Scholarship
Montclair, New Jersey
United States of America
ORCID 0000-0003-2116-5720

Email john.larocco@ronininstitute.org

http://dx.doi.org/10.61618/AOFP5085

Abstract

Line launchers are devices that have been used for centuries for maritime rescue operations. The typical implementation is the use of a gun, rocket, or mechanical launcher to hurl a grappling hook or flotation buoy for stranded ships and overboard sailors. Microgravity offers analogous use cases, ranging from microsatellite operations to space debris interception. As such, the Lachesis line launcher is a handheld device that is purpose-built for microgravity applications. After the user pulls the trigger, a laser ignites a smoothbore rocket-propelled projectile which carries a nylon line behind it. Angled threads in the barrel provide the spin and stability that is typically only achieved by conventional rifling. To reduce weight, most components are 3D-printed out of polylactic acid (PLA), a biodegradable and light plastic. With a total weight of 68 g and a projectile kinetic energy of 0.127 J, the Lachesis line launcher presents an effective, potential option, even with contemporary operational constraints. The design combines several proven principles to demonstrate the viability and use case for an updated line launcher in orbital operations.

KEY WORDS*: line launcher, microgravity, rescue device, object capture*

Introduction

Line launchers are a maritime rescue device used in rescue operations for centuries (Spangler & Homer, 2015). The typical implementation is the use of a gun, rocket, or mechanical launcher to hurl a grappling hook or flotation buoy for stranded ships and overboard sailors. Microgravity offers analogous use cases, ranging from microsatellite operations to space debris interception. As such, the Lachesis line launcher is a handheld device purpose-built for microgravity. After the user pulls the trigger, a laser ignites a smoothbore rocket-propelled projectile carrying a nylon line behind it. Angled threads in the barrel provide spin and stability typically only achieved with conventional rifling. With improved materials and technologies, the launcher presents a safe potential option even with contemporary operational constraints. The Lachesis line launcher combines several proven principles to demonstrate the viability and use case for an updated line launcher in orbital operations.

As maritime line-launchers are widely used, International Convention for the Safety of Life at Sea (SOLAS) regulations mandate certain ships carry a line-launcher aboard, but space law is still developing (Snook, 1974; International Maritime Organization, 1974). Outer space offers several potential use cases for a line launcher. The first is the same as its maritime counterpart: rescuing personnel and securing objects that are adrift. Current extravehicular activity is performed at the end of a robotic arm, but future spacecraft and space stations may not include such a feature. Handholds are often designed so that an astronaut always has a single hand in contact with the craft, thus tools should be designed for single-handed use where possible. Similarly, a line launcher could be used to deploy specialized sensors, intercept incoming objects, and secure components (Liu, Qiu, Li, & Yang, 2017; Zhao, Liu, & Wu, 2020; Sizov & Aslanov, 2020). Outside of the scope of handheld use, a space-based line launcher system could be mounted on a satellite as a capture or tether system (Sizov & Aslanov, 2020).

However, object capture devices in microgravity have relied on expensive, complex systems, such as high-speed robotic arms to grasp fast-moving micro-debris. Due to the quality and precision required, the costs of the sensors and actuators are often the most expensive parts of the system (Liu, Qiu, Li, & Yang, 2017; Zhao, Liu, & Wu, 2020). A line launcher requires range and accuracy. As the projectile is still attached to the launcher, recoil like that from a firearm or compressed gas gun could throw off the user's aim. A purely mechanical launcher, such as a crossbow or slingshot, would need to be resistant to the extreme temperatures present in space. Electromagnetic launchers would require capacitor banks and thermal management. Rocket-based line launchers can potentially allow for a longer range since they slowly burn fuel over a longer period of acceleration (Woodford, 1932; Ambur, Jaunky, Lawson, Knight, & Lyle, 2004). With an equivalent propellant weight and a similar projectile size, a rocket could cover a longer distance than a conventional firearm. A rocket launcher would lack the recoil of a firearm, eliminating the recoil force on a user or platform in microgravity.

Compared to the alternatives, a solid fuel rocket-driven line launcher would be small, compact, and efficient for a more compact device (Sizov & Aslanov, 2020). Despite the apparent simplicity, a line launcher for microgravity required re-invention of its terrestrial, historical counterparts. A microgravity-based line launcher would require a rocket, a tether, an ignition system, a casing, a spin-stabilization method, and a reliable ignition system. While historical line-launchers offer a starting point, maritime and terrestrial devices were designed for fundamentally different conditions. Thus, the Lachesis line-launcher was designed.

The Lachesis line launcher is named after one of the Greek Fates, the three goddesses that determined the lives of mortals. Clotho spun the thread of life, Lachesis measured it, and Atropos cut it (Graves, 2012).

The line launcher required a thin, strong thread, which could be used in lifesaving applications (Skoog, 2019). As the device could lengthen human survival, the name of Lachesis was chosen. While the name is archaic, the technologies utilized are more contemporary. The objective was to design a handheld line launcher for outer space.

Literature Review

Historical Line-Launchers

Line launchers are rescue devices originally designed for maritime or sailing applications. At their most rudimentary, they consist of a launcher and a line attached to a profile, which is intended to be throw further than human strength allows, used to discharge rescue buoys for overboard sailors or grappling hooks for towing vessels (Rundle, 1937; Niblack, 1927). Examples include the Victorian-era Lyle cannon, shown in Fig. 1 (Spangler & Homer, 2015).

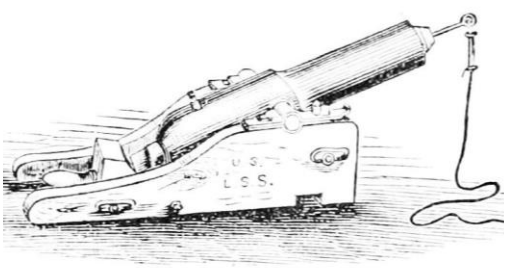

Figure 1: A Lyle cannon used by the United States Coast Guard (Wikimedia Foundation, 2022).

Another example was the British Schermuly pistol-rocket apparatus shown in Fig. 2 (Parade Antiques, 2023; Rundle, 1937).

Figure 2: A preserved Schermuly pistol-rocket apparatus **(Parade Antiques, 2023)**.

Presently, SOLAS regulations mandate certain ships possess a line-launcher (Snook, 1974; International Maritime Organization, 1974). Outside of rescue devices, rocket-launching pistols were also used as weapons.

Rocket Pistols

Figure 3: An M. B. Associates "Rocketeer" gyrojet pistol in original packaging **(Wikimedia Foundation, 2023)**.

The M. B. Associates (MBA) Rocketeer pistol shown in Fig. 3 provides an example of a pistol discharging a gyrojet, a rocket engine inside a metal slug (Carpenter, 2010). The cost and complexity of the system made the Rocketeer pistol expensive and unreliable (Dillon & Thornton, 1967). Launching a rocket from a “gun” or rigid casing tube enables it to have a greater initial velocity, as the pressure from the heated exhaust behind it exerts additional force (Woodford, 1932). A short propellant burn time is optimal for ensuring a stable and accurate gyrojet trajectory. However, launching a rocket from inside a container or gun-barrel helps ensure consistent outcomes for each (Woodford, 1932) (Carpenter, 2010).

Spin Stabilization

As with bullets, rockets can be spin-stabilized since a rotating projectile has a longer effective range. Conventional firearms include rifling, but rockets (including gyrojet rounds) typically require more than one angled nozzle to obtain the same result (LaRocco, Throwing a line to Tomorrow, 2021; Carpenter, 2010). Without the angled rocket nozzles, gyrojets would be unable to spin-stabilize. Developments in another type of launcher could potentially stabilize a smoothbore projectile, such as a shotgun slug or single-nozzle gyrojet round. Foam dart blasters are toys for which hobbyists have developed novel attachments, including analogs to conventional rifling to improve accuracy (Captainslug, 3; Phillips, 2022).

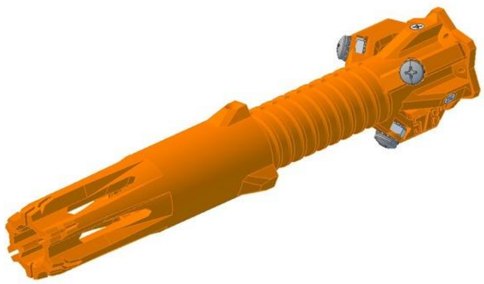

*Figure 4: Muzzle attached rifled 3D-printed barrel for foam dart blasters **(Captainslug, 3)**.*

As shown in Fig. 4, one such analog is the use of strings in a barrel attachment, pulled taut at slight angles relative to the projectile's direction of travel. While this applies a slight friction, it serves an analogous function to rifling in a smoothbore projectile. Other variants of the "soft rifling" concept use mechanical roller bearings. A potential benefit to a rocket is that due to the friction encountered, the rocket will accelerate to a higher velocity while leaving the barrel. The concept has not yet been applied broadly outside of the foam dart hobbyist community.

Lines and Tethers

A line launcher requires a secure tether to perform its role. Historical line launchers used rope or buoyant cable, strong enough to secure ships in stormy seas. Current nautical lines, such as Spectra ® and Dyneema ®, would be bulkier and heavier than more novel materials. A smaller, handheld line-launcher would require different considerations in microgravity. Fullerenes have the highest documented tensile strength, although fabrication of single carbon nanotubes or graphene ribbons has proven costly. Commercial fishing line could be an effective substitute, in lieu of affordable fullerene lines.

Rocket Ignition

A line requires a means to carry it. While rockets and guns were used previously, reliable ignition is integral to the device's function. Firearm blanks and electric ignition are widespread, but have potential problems in an orbital context. An alternative is optical ignition, i.e., the use of a laser to ignite the rocket. Shown in Fig. 5, optical ignition has already been used as a substitute for conventional primers in a line of Voere's hunting rifles (Voere, 2015).

Figure 5: Voere laser ignition system for bolt-action rifle **(Voere, 2015)**.

Optical ignition does not require a direct connection between the rocket and launcher, making it suitable for ignition of the line-carrying rocket.

Figure 6: Soviet TP-82 cosmonaut survival pistol **(Wikimedia Foundation, 2023)**.

Device Housing and Casing

Using a lighter material to fabricate the launcher would reduce its mass, which would also reduce payload-dependent launch fuel costs. As shown in Fig.6, a precedent for firearms in space is the Soviet-designed TP-82 cosmonaut survival pistol, to assist survival after landing by launching flares, defending against predators, and hunting small game, shown in Fig. 6 (Popenker, 2022). Many line launchers are stored disassembled during transport on vessels where cargo space is at a premium, so modular assembly was preferred. Using 3D-printed plastics for both the launcher and the rocket such as polylactic acid (PLA) could enable rapid, low-cost fabrication. Even if the line launcher or rocket is “dropped” in orbit, PLA degrades in ultraviolet (UV) light, instead of becoming a persistent orbital hazard (Nogales, et al., 2018). These considerations drove the development of two sequential prototype line launchers.

Methods

Prototype 1

Two separate prototypes of Lachesis were constructed. The first prototype was a 3D-printed, modular pistol with laser ignition, textile rifling, a nylon line, and PLA composition. All plastic parts were 3D-printed with PLA with a 20% infill. The rear of the pistol contained an opened slot to fit a laser pointer. All parts were designed to reattach with a friction fit, shown separately in Fig. 7.

Figure 7: Primary 3D printed prototype components including barrel, grip, magazine, and projectile.

The external laser pointer was bulky, but it contained the essential components: batteries, circuitry, and an activation switch. A final iteration would have the components fully integrated, but basic testing commenced with the aperture-mounted laser. By aligning the laser in position, it would be pointed directly down the nozzle of the rocket. The continuous-wave 450 nm laser produced 50 mW of power. The laser system required ~3 s to reach maximum intensity. With electronics positioned inside, the assembled system is shown in Fig. 8.

Figure 8: Lachesis prototype 1 fully assembled.

A thin sheet of acrylic was positioned between the laser collimating lens and the rocket. Based on models from the open-source Ronin Rocket Repository, two 3D-printed PLA rocket engines were tested: Phi (9 mm) and Tau (5.7 mm) (LaRocco, Ronin Rocket Repository, 2022). The mass of the standard dart was 0.2 g.

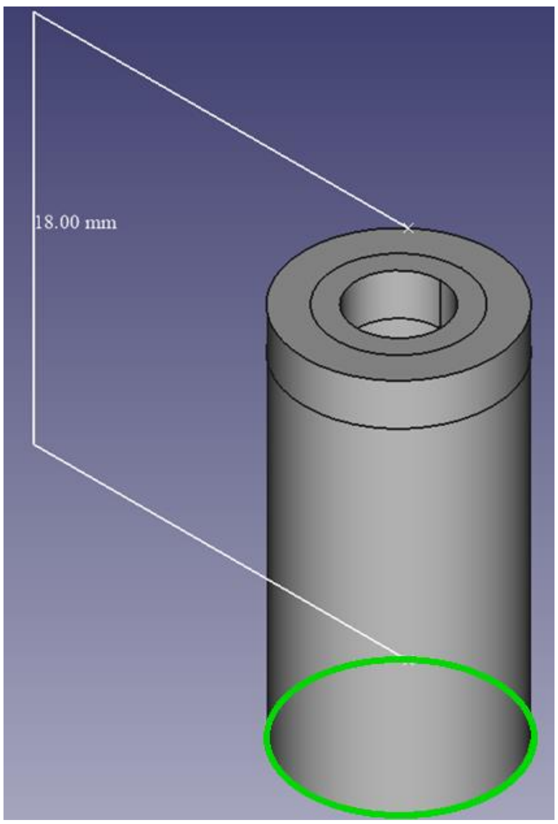

Figure 9: Phi rocket engine (18mm in diameter, with a 4.5mm radius).

The Phi rocket engine is shown in Fig. 9. Phi series rockets would be wrapped in electrical tape to increase friction and engage rifling, while Tau series rockets would be embedded within short foam darts (12.7 mm in diameter and 38 mm in length) to provide additional thrust. For the Phi series projectiles, the line was attached via looping the line through the rubber portion of the dart and tape.

Figure 10: Phi rocket engine within dart.

Shown in Fig. 10, the total mass of a Phi rocket dart was 0.35 g. As shown in Fig. 11, the Tau series rocket was inserted within the dart, allowing the line to be threaded through apertures in the dart's foam head. The total projectile mass for a Tau rocket dart was 0.25 g. Both were tried independently to determine which was more reliable. The velocity of each was measured via ballistic chronograph.

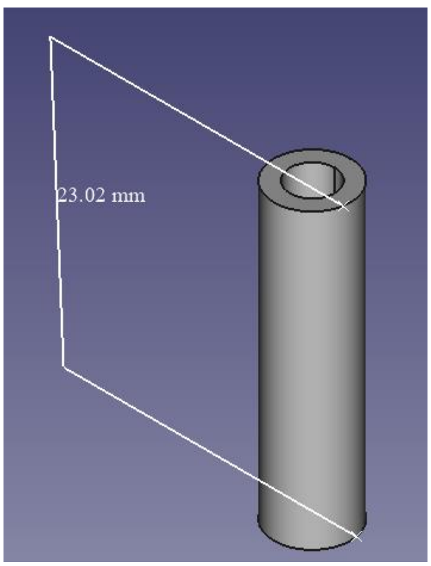

Figure 11: Tau rocket engine (6mm in diameter, 23mm in total height).

Prior line launchers had either an under-barrel or barrel-mounted spool of line. An external mounting position could potentially result in a tangled line if mishandled. The line would need to be spooled or coiled in such a way that it could be rapidly inserted or mounted onto the launcher. As the launcher was designed in the likeness of a pistol, placing the line in the "magazine" was attempted. A bracket at the bottom of a detachable "magazine" was used as a line tie-off point, as shown in Fig. 12.

Figure 12: Magazine-based assembly containing line, spool, and rocket.

Monofilament KastKing (NY, USA) fishing line with a 0.4 mm diameter was used as the test line. The line snaked from the nose of the projectile down into the “magazine” spool. The potential rapid ignition and burn rate was within 100 ms. Based on prior testing, the line would not be burnt behind the rocket.

Calculation

Refinement of a handheld line launcher required complex calculations regarding force diagrams, propellant burn rates, and orbital kinematics. In microgravity, a handheld tethering system was especially a complex problem. However, the core function of a line launcher is delivering a line-carrying projectile with consistent velocity. As such, refining the first step was the most important part of early-phase prototyping. The design had to ensure that the projectile could be reliably launched with consistent velocity at a constant distance, with other factors being controlled.

The initial test methodology involved positioning a ballistic chronograph in front of the launcher. The rocket was secured at the muzzle with a friction fit. The laser was positioned behind the rocket nozzle at a distance of 5.1 cm, and was protected by a thin acrylic sheet. Fishing line atop the rocket ensured it would travel through the chronograph. The tests were performed to confirm they could successfully ignite. Initial results were used to inform the design of a second prototype.

A D-class model rocket was used as the upper boundary for line-carrying rocket performance, with a total impulse of 10.01–20.00 Ns (National Association of Rocketry, 2023). As with traditional model rocket engines, black powder was used as the propellant in both rocket engines. For the Phi engine, 1.16 g of black powder was used. For the Tau engine, 0.33 g of black powder was used. Conventional firearm cartridge velocities were used to estimate the maximum kinetic energy of each rocket. Phi was approximated to a .38 Special cartridge, with a kinetic energy of 270 J while Tau was approximated to a .22 LR cartridge, with a kinetic energy of 180 J. These values were calculated for contemporary smokeless powder, rather than traditional black powder (SAAMI/ANZI, 1992). As such, the maximum effective kinetic energy could be reduced to less than half of the recorded values (LaRocco & Lehr, Jeju Archive of Mechanical Launchers, 2022). The burn time was assumed to be approximately 100 ms of ignition, based on the MBA gyrojet pistol (Carpenter, 2010). The Tsiolkovsky rocket equation is given below in Eq. 1 (Dvornychenko, 1990).

$$\Delta v = v_f - v_i = v_e \log\left(\frac{m_i}{m_f}\right), \text{ (1)}$$

where Δv is the change in velocity, v_f is the final velocity, v_i is the initial velocity, v_e is the effective velocity, m_i is the initial mass, and m_f is the final mass.

The encasing of each rocket in a short foam dart and tape would add to the friction prior to departing the barrel, due to engaging the soft rifling. It was hypothesized that the rocket would reach its maximum velocity at the end of the barrel, analogous to the muzzle velocity of a firearm. A ballistic chronograph was positioned at the prototype's muzzle. The projectile consisted of the rocket, powder propellant, electrical tape, and a foam dart. Each projectile was weighed before and after launch to calculate its specific impulse and kinetic energy. Kinetic energy, E_k, was calculated using Eq. 2, where m is the object mass and v is the velocity (Tipler & Mosca, 2007).

$$E_k = \frac{1}{2} m v^2 \text{ (2)}$$

Tests were performed with and without soft rifling to estimate the friction on the projectiles. The soft rifling consisted of a hollow cylinder 2.5 cm long with holes at a 15 º angle to the horizontal plane, to impart rotational friction. Twine or fishing line was threaded through each of four pairs of holes.

The chronograph's distance from the end of the barrel was used to ensure the maximum velocity was reached. In the event the projectile failed to clear the barrel, the configuration was noted. In the event where the onboard propellant was insufficient to allow the projectile to clear the rifling or the dart contained no rocket, a pneumatic launcher was used instead. The secondary launcher was sufficient to accommodate the mass of the projectile. The pneumatic launcher could be positioned behind the launch unit, just as with the laser pointer. Otherwise, the configurations were identical.

Prototype 2

The second prototype integrated the electronics and a different line launcher configuration. Positioning the line behind the projectile resulted in continuous failures during both rocket and pneumatic launches. In the case of rocket launches, the fishing line melted due to the heat of the exhaust. During malfunctions from pneumatic launches, the line snagged. A more conventional line storage configuration was used instead, where the line was coiled in a plastic ring around the muzzle. To secure the line to the barrel, 10 cm of soft rifling was attached to the coil to create a friction fit between the component and the barrel. Epoxy was used to additionally secure it. Two variants of soft rifling, one with thick twine and the other with fishing line, were employed. To reduce the chance of friction stopping the projectile entirely, a single soft rifling segment of 2.5 cm was used during testing.

Figure 13: Lachesis prototype 2 with projectile, thicker wire, and muzzle-mounted line spool.

The entire device is shown in Fig. 13. To improve the weight and balance of the device, the optics and the control circuitry were positioned at the rear of the launcher. To improve grip ergonomics and stability, the batteries were relocated in the handle, along with 55 g of metal screws. A heavier gauge wire was used to accommodate the higher electrical current in the electrical circuit, as shown in Fig. 14. A 3D-printed cone was used to create a friction fit for the collimator lens in front of the laser diode. A button switch connected the batteries and laser diode driver circuit, which was used as the trigger.

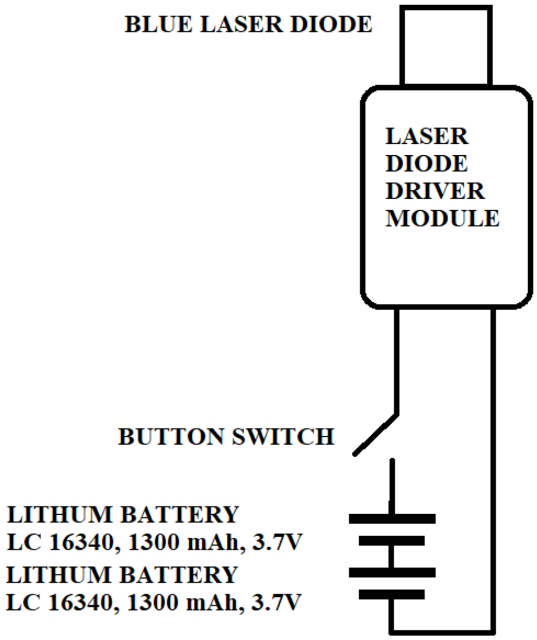

Figure 14: Electrical schematic of optical ignition circuit, including 447nm blue laser diode (MDL-XS-447).

The body of the prototype was held together with a friction fit, allowing it to be safely disassembled and stored as necessary. The length of the assembled prototype was approximately 310 mm. The total mass of the prototype was 13 g, for a total mass of 68 g, including the metal screws. The two prototypes are compared against each other in Fig. 15.

Figure 15: Two prototype line launchers, with Prototype 1 on bottom and Prototype 2 on top.

The tests were repeated with the second prototype at 1 m, comparing the effects of soft rifling and projectile configuration. The performance factors were the soft rifling and the projectile configuration. The primary analysis was conducted with the second prototype. The first tests conducted were to compare use of the thick twine soft rifling, fishing line soft rifling, and no soft rifling. Three shots with each projectile were attempted. If the first two attempts at rocket ignition failed, they were launched pneumatically. In the event of a launcher failure or malfunction, the remainder of the tests would be conducted with the pneumatic launcher. A two-way analysis of variance (ANOVA) was conducted with post-hoc tests in Python.

Results

The two primary conditions included the rifling type (no rifling, nylon line-based rifling, and twine-based rifling) and projectile time (basic dart, dart with Tau rocket, and dart with Phi rocket). As shown in Table 1, the presence of rifling lowered the average velocity by over 20 ms^{-1} for standard darts. The use of rocket and dart hybrid projectiles also indicated a drastic drop in velocity due to the friction increase. By the time the projectile left the barrel, the entire propellant had been expended. The average time from trigger pull to launch was 3.2±1 s.

Rifling	**Dart**	**Tau**	**Phi**
None	41.4±1.9	31.9±1.9	25.6±3.9
Nylon	21.2±2	6.4±1.1	6.9±0.5
Twine	22.5±1.9	7.9±0.5	6.9±1.5

Table 1: Average Velocity (ms^{-1}) and Standard Deviation of Rifling and Projectiles at 1 m

The measurements include the average mean from three measurements and the standard deviation across observed measurements. Using Eq. 2, the highest projectile kinetic energy was 0.171 J for a standard dart. The highest kinetic energy was 0.127 J for a rocket projectile, substantially less than for the foam dart projectile's maximum kinetic energy. The ANOVA revealed significant differences in the observed results. Each variable is a sub-heading in Table 2, listing the two variables (rifling and projectile type), and their interaction. The first column of Table 2 shows the Sum of Squares, corresponding to the total size of each effect. The next column includes the degrees of freedom. The second column in Table 2 shows the degrees of freedom (*df*), is based on group means and sets. The third column includes the F-score, a statistical measure used to test each hypothesis. The final column in Table 2 shows the probability, the *p* score. If the value is less than 0.05, the result is statistically significant.

	Sum of Sq	df	F	PR(>F)
C(rifling)	2638.732	2	339.6861	5.08E-15
C(projectile)	1219.743	2	157.0185	4.04E-12
C(rifling):C(projectile)	45.14148	4	2.90555	5.12E-02
Residual	69.91333	18	NaN	NaN

Table 2: ANOVA Results for Velocity Measurements

As shown in Table 2, the interaction of the two primary effects (rifling and projectile type) was not statistically significant, albeit by a close margin. The added mass of even a small rocket (such as Tau) was enough to add a significant velocity. The implications of the dramatic drop in velocity warrant a closer investigation into optimization of projectile design and soft rifling.

Discussion

The re-invention of the line-launcher for microgravity extends well beyond a single, handheld device. The Lachesis system demonstrates a successful and novel integration of independently verified technologies. The concept of a line launcher validates a general-purpose projectile launcher with applications beyond rescue, including aerospace, industry, and defense. For defense and industry, the use of optically ignited single-nozzle gyrojets with “soft rifling” could greatly reduce gun barrel corrosion in small arms (Kumar, Kalra, & Jha, 2022). In aerospace, similar units could be mounted on the bodies of spacecraft for object capture or antennae deployment (Sizov & Aslanov, 2020; Zhao, Liu, & Wu, 2020). The applications of the device are far too numerous to list, although certain limitations must be addressed.

Limitations

The study had several primary limitations. The first limitation is the lack of more complex kinematic models and simulation. The second limitation with the soft rifling is that roller-bearing based “rifling” may have a consistently superior performance, even with smoothbore and soft projectiles. A third limitation is the potential reliability of the launcher under stress. A fourth limitation is the drag induced by the rifling, which may put into question the need for it. A fifth limitation is the nature of the line projectile itself, as prior line launchers used grappling hooks or flotation buoys to ensure a reliable attachment or consistent positioning. A sixth limitation is the short span of line included in the study. A final, seventh potential limitation is the relative weakness of the nylon fishing line compared to traditional rope on line launchers. However, these problems could be addressed in future work.

Future Work

A future investigation could improve upon the points raised. More complex models and calculation can be used to refine the core device demonstrated here. The physical prior tests were performed with space constraints, precluding the use of longer lines. The comparison of soft rifling against roller bearing rifling, as well as variants of each, is perhaps the largest change (Phillips, 2022). The existing soft rifling dropped the velocity well below that reported using darts in pneumatic foam dart blasters (Phillips, 2022). This may be attributable to a single longer segment with too much friction, as opposed to several smaller ones, as used in comparable foam dart blasters (Captainslug, 3). The second major improvement is substantially improving the reliability of the rocket ignition mechanism and ~3 s warmup period with the laser. While a pneumatic system was included for preliminary tests, a conventional rocket engine offers far more advantages in line-carrying distance (Skoog, 2019). Protecting optical components could be accomplished by substituting a different type of acrylic or transparent material between the laser and rocket, potentially including a sacrificial one on the rear of each projectile.

The Voere laser-ignition system uses a translucent material where a primer would be in a conventional rifle cartridge, so a similar material could be positioned at the nozzle of each rocket, even if it was sacrificial (Voere, 2015). As with other optically-ignited rocket launch systems, a pulsed laser may be more immediate and reliable than a modified continuous-wave laser. Substituting the continuous-wave laser with another mechanism, such as photo-ignition, could greatly simplify the electronics and reduce the cost (Badakhshan, Danczyk, Wirth, & Pilon, 2011). An optimized fuel mix could similarly improve range and power, allowing a more consistent rocket acceleration (Woodford, 1932).

Similarly, the line itself could benefit from a stronger material composition and a novel adhesion mechanism. The nylon fishing line could be substituted with carbon nanotube and fullerene-based materials (Bai, et al., 2018). The mechanism of line attachment to the target was unexplored in the paper, as the launch system had to be demonstrated first. While prior line launchers used grappling hooks, new materials present novel possibilities. Synthetic setae, which use van der Waals forces to adhere to materials like a gecko's foot, could greatly increase attachment reliability compared to chemical adhesives or mechanical protrusions (LaRocco, Evaluation of synthetic setae pads for dry attachment of an ultrasound transducer, 2019). Such materials can be cheaply and commercially procured. Lighter than both the Soviet TP-82 and British Schermuly pistol-rocket apparatus, the Lachesis line launcher can potentially serve as a lighter tool for space and airborne emergency response (Snook, 1974).

Conclusions

The described device reinvents the classic line launcher for outer space. While the contemporary maritime economy still uses line launchers, the commercial spaceflight economy has not yet adopted them. As with the terrestrial counterpart, line launchers offer operational utility, including object capture, antennae deployment, and rescue. The rocket-based Lachesis system prototype possesses several unique advantages relative to prior launchers. It possesses a light mass (68 g with metallic components added for balance) a contactless optoelectronic launch system, a novel method of stabilizing the projectile, and the ability to be disassembled and reassembled. The use of 3D-printed PLA components also ensures the unit would be eroded by ultraviolet light in orbit, to ensure it does not linger as space debris. Improvements to the launch system, the line design, the soft rifling, and the materials would be iterative improvements upon a proven concept. Despite these relative shortcomings, the Lachesis line launcher reintegrated several proven principles together to demonstrate the viability and use case for an updated line launcher in orbital operations.

Acknowledgements

The author would like to thank those who have provided preliminary feedback on this document. Computer models and data used in this work are available at: https://github.com/javeharron/lachesislinelauncher

About the author

John LaRocco is a research scientist based in Columbus, Ohio, USA. He completed BS in engineering science in 2008 at The College of New Jersey. In 2011, he completed a MS in Electrical and Computer Engineering at Rowan University. He completed his PhD in Electrical Engineering at the University of Canterbury in 2015. He completed postdoctoral research at the University of Texas-San Antonio. He has worked in research and industry in the US, Singapore, South Korea, and New Zealand. His research interests include electronic signal processing, military history, and the role of firearms in research and industry.

References

Ambur, D., Jaunky, N., Lawson, R., Knight, J. N., & Lyle, K. (2004). A gas-actuated projectile launcher for high-energy impact testing of structures. *Proceedings from the Structural Dynamics, and Materials Conference and Exhibit*, 1385. doi:10.2514/6.1999-1385

Badakhshan, A., Danczyk, S., Wirth, D., & Pilon, L. (2011). *Photo-ignition of liquid fuel spray and solid rocket fuel by carbon nanotube utilizing a camera flash.* Edwards AFB: AIR FORCE

RESEARCH LAB EDWARDS AFB CA PROPULSION DIR. Retrieved from https://apps.dtic.mil/sti/pdfs/ADA571235.pdf

Bai, Y., Zhang, R., Ye, X., Zhu, Z., Xie, H., Shen, B., . . . Zhang, S. (2018). Carbon nanotube bundles with tensile strength over 80 GPa. *Nature nanotechnology, 13*(2018), 589-595. doi:10.1038/s41565-018-0141-z

Captainslug. (3, December 2017). *Captainslug. (n.d.). Nerf Caliburn - scar barrel by captainslug.* Retrieved April 28, 2023, from Thingiverse: https://www.thingiverse.com/thing:2686643

Carpenter, M. (2010). *An Introduction To MBA Gyrojets and Other Ordnance.* MRC3 Publishing.

Dillon, D. J., & Thornton, J. I. (1967). Identification Notes on the Gyrojet Weapons System. *(1967).. Journal of the Forensic Science Society, 7(3), 146-150., 7*(3), 146-150. doi:10.1016/S0015-7368(67)70396-5

Dvornychenko, V. N. (1990). The Generalized Tsiolkovsky Equation. *NASA Conference Publication, 3102*(1), 449.

Graves, R. (2012). *The Greek Myths: Penguin Classics Deluxe Edition).* New York City: Penguin.

International Maritime Organization. (1974). *International Convention for the Safety of Life at Sea (SOLAS), 1974.* Retrieved April 19, 2023, from International Maritime Organization: https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

Kumar, D., Kalra, S., & Jha, M. S. (2022). A concise review on degradation of gun barrels and its health monitoring techniques. *Engineering Failure Analysis*, 106791. doi:10.1016/j.engfailanal.2022.106791

LaRocco, J. (2019). Evaluation of synthetic setae pads for dry attachment of an ultrasound transducer. *Proceedings of the IEEE Healthcare Innovations and Point of Care Technologies Conference*, 99. doi:10.1109/HI-POCT45284.2019.8962885

LaRocco, J. (2021, October 7). *Throwing a line to Tomorrow*. Retrieved April 28, 2023, from Ronin Institute: https://ronininstitute.org/throwing-a-line-to-tomorrow/5859/

LaRocco, J. (2022, November 21). *Ronin Rocket Repository*. Retrieved from Github: https://github.com/javeharron/roninrockets

LaRocco, J., & Lehr, C. (2022). *Jeju Archive of Mechanical Launchers.* Jeju: Ronin Institute. doi:10.13140/RG.2.2.11817.47205

Liu, Z. Q., Qiu, H., Li, X., & Yang, S. L. (2017). Review of large spacecraft deployable membrane antenna structure. *Chinese Journal of Mechanical Engineering, 30*(6), 1447-1459. doi:10.1007/s10033-017-0198-x

National Association of Rocketry. (2023, April 19). *Model Rocket Safety Code*. Retrieved from National Association of Model Rocketry: https://www.nar.org/safety-information/model-rocket-safety-code/

Niblack, A. P. (1927). Summary of Data on Safety of Life at Sea and Lifesaving. *The International Hydrographic Review*. Retrieved from https://journals.lib.unb.ca/index.php/ihr/article/download/27839/1882520595

Nogales, C., Grim, B., Kamstra, M., Campbell, B., Ewing, A., Hance, R., . . . Parke, S. (2018). MakerSat-0: 3D-printed polymer degradation first data from orbit. *Proceedings of the Annual AIAA/USU Conference on Small Satellites*, 1-6. Retrieved from https://digitalcommons.usu.edu/smallsat/2018/all2018/434/

Parade Antiques. (2023). *C1930 Schermuly Pistol rocket apparatus for line throwing. Parade Antiques - If you think antiquies are boring, think again*. Retrieved April 18, 2023, from Parade Antiques: https://paradeantiques.co.uk/militaria/equipment/c1930-schermuly-pistol-rocket-apparatus-for-line-throwing

Phillips, B. (2022, Feb 22). *Nerf Blaster Rifling Tested from Shanye and Dsfrick! YouTube. Retrieved April 28, 2023, from*. Retrieved April 18, 2023, from Youtube: https://www.youtube.com/watch?v=tHo2WirPaKQ

Popenker, M. (2022). *Modern Firearms*. Retrieved April 18, 2023, from view-source:https://modernfirearms.net/en/shotguns/russia-shotguns/tp-82-eng/

Rundle, C. H. (1937, April). His Majesty's Coastguard—Its Life-Saving Duties. *Public Administration, 15*(2), 138-143. doi:10.1111/j.1467-9299.1937.tb02464.x

SAAMI/ANZI. (1992, November 24). *American National Standard Z299.1-1992.* Retrieved from Scribd: https://www.scribd.com/document/241716953/SAAMI-Z299-3-Velocity-and-Pressure-Data-Centerfire-Pistol-and-Revolver

Sizov, D. A., & Aslanov, V. S. (2020). Space Debris Removal with Harpoon Assistance: Choice of Parameters and Optimization. *Journal of Guidance, Control, and Dynamics, 44*(4), 767-778. doi:10.2514/1.G005484

Skoog, A. I. (2019). Lifesaving rockets in Sweden. A century of operation. *Acta Astronautica, 162*(1), 511-525. doi:10.1016/j.actaastro.2019.06.018

Snook, R. (1974). River and Sea Search and Rescue. *Medical Aid at Accidents*, 93-101. doi:10.1007/978-94-011-8042-9_14

Spangler, J., & Homer, W. (2015). Guns to Save Lives: An Introduction to Line Throwing Guns. *American Society of Arms Collectors Bulletin, 111*(1), 90-125. Retrieved from American Society of Arms Collectors.

Tipler, P. A., & Mosca, G. (2007). *Physics for scientists and engineers.* Macmillan.

Voere. (2015). *Voere*. Retrieved April 28, 2023, from Laser Ignition: http://www.voere.com/en/history/laser-ignition.htm

Wikimedia Foundation. (2022, November 22). *Lyle gun*. Retrieved April 28, 2023, from Wikipedia: https://en.wikipedia.org/wiki/Lyle_gun

Wikimedia Foundation. (2023, April 7). *Gyrojet*. Retrieved April 28, 2023, from Wikipedia: https://en.wikipedia.org/wiki/Gyrojet

Wikimedia Foundation. (2023, April 3). *TP-82*. Retrieved April 28, 2023, from Wikipedia: https://en.wikipedia.org/wiki/TP-82

Woodford, L. D. (1932). The History of the Rocket Motor. *Ohio State Engineer, 16*(3), 21. Retrieved from http://hdl.handle.net/1811/34958

Zhao, P., Liu, J., & Wu, C. (2020). Survey on research and development of on-orbit active debris removal methods. *Science China Technological Sciences, 63*, 1-23. doi:10.1007/s11431-020-1661-7

Comparing Reports with Actual Missing Persons' Footwear

Robert Speiden, BSE [1,2], Brian Cohan, MS, PE [1,3], Joel M. Serrano, PhD [1,2]
[1]Search & Rescue Tracking Institute, [2]Blacksburg Volunteer Rescue Squad, [3]Piedmont Search & Rescue
United States of America
Email: robspeiden@blacksburgrescue.org

ABSTRACT

Search and rescue resources conduct missions for tens of thousands of persons annually. Visual trackers constitute one of many resources involved in searches for missing persons. Original research compares report details with actual find characteristics of 428 missing persons' footwear (or lack thereof) from 1970 to 2024. Footwear report details such as type, brand, color, and size proved correct for 78%, 87%, 88%, and 91%, respectively, when missing persons were found. Paradoxical undressing, voluntary and involuntary removal, and cognitive impairments contributed to 25% of all subjects being found unshod. Data forms and a database were created to collect misper footwear information. A case study illustrates the beneficial application of footwear investigations. This new research provides a unique foundational understanding of how footwear information can be applied to search missions.

KEY WORDS: *Search and Rescue, Tracking, Shoe, Boot, Barefoot, Unshod, Signcutting*

INTRODUCTION

This study took aim at several goals including conducting original research to gather and compare report and found footwear data, constructing a foundational database of footwear information for more research, communicating results of findings, providing motivation for pursuing subject footwear information, demonstrating the application of footwear information at a search, providing a foundation for developing tracking tools, and suggesting improvements, including a new document for footwear investigations.

In 2023, the United States (U.S.) population was estimated at 335 million (USCB, 2024), and that population is expected to purchase a wide variety of footwear types, colors, styles, and sizes. From 2010 through 2019, U.S. citizens purchased over two billion pairs of shoes annually from 2010 through 2019 (Statista, 2024). William Bodziak (2017, p. 294) observes, "The large number of shoes sold per year combined with shoes purchased in prior years equates to many billions of shoes in the US." Regarding the evolution of the human foot and footwear, Hawes and Sovak (1994, p. 1213) note, "The human foot has evolved from a generalized grasping organ to an organ specialized for weight-bearing and locomotion. To facilitate these functions, man has clad the foot in a variety of coverings to afford protection and warmth. In today's society, these foot coverings have become increasingly specialized for a variety of tasks..."

Though a small portion of the entire population, hundreds of thousands of persons are reported missing every year in the U.S. alone and certainly more happen world-wide (GoC, 2023; NMPCC, 2022; Shalev & Humer, 2022). The Federal Bureau of Investigation's (FBI) National Crime Information Center annual statistics for 2015 through 2022 recorded between 521,705 and 651,226 missing persons reports (FBI, 2016, 2017, 2018, 2020a, 2020b, 2021, 2022, 2023) resulting in an annual mean of 595,873. Though not all reports result in organized search efforts for missing persons (also referred to herein as subjects or mispers), search resource deployments occur thousands of times every year in the U.S. For example, the National Park Service alone conducted an average of 4090 search and rescue operations per year from 1992 through 2007 (Heggie & Amundson, 2009).

Similar trends occur in other countries as well. For example, England and Wales (E&W) receive over 300,000 calls regarding missing persons, and initiate approximately 250,000 incidents per year (NCA, 2014, 2015, 2016, 2017, 2019a, 2019b, 2020, 2021, 2022, 2023; NPIA, 2011; SOCA, 2013). Additional countries experience a similar high volume of misper calls to policing agencies (GoC, 2023; NMPCC, 2022; Shalev & Humer, 2022).

One of the first tasks in a methodical search and rescue (SAR) mission is gathering subject information. Koester (2008, p. 4) writes "Investigation is the tool that helps determine the specifics of an individual." Subject information includes reports of clothing (including footwear), belongings, and other items that might inform searchers about potentially relevant clues. While common sense dictates that one's footwear is the most common contact point between a person and the ground, missing person investigations don't always gather footwear information. Focusing attention to that person-ground interface can accelerate the find. Due to the lack of ability to find or interpret them, tracks are often overlooked or undervalued at searches. Bodziak (2017, p. 6) suggests, "What is not looked for will not be found."

This research lays the foundation for perpetual SAR tracking tools development. Visual tracking resources (trackers) endeavor to find, interpret, and follow the missing person's tracks. In addition to other types of clues, trackers and searchers often find footwear impressions or footprints during search efforts. Research is being conducted on clues found during search efforts. Preliminary findings from 503 searches indicate that subjects' tracks were found on 84 (17%) of those searches. Of those 84 searches, trackers found tracks on 67% of them and non-trackers found tracks on 19%. After a footprint is found, trackers must assess relevance to the subject. Whether the missing subject moves shod or unshod, information about their footwear (e.g., nominal size, model, or dimensions) can assist searchers in track interpretation by increasing accuracy, confidence, and ability to articulate track interpretation. Through processes of comparison and elimination, subjects' tracks can be distinguished from searchers' tracks or others that were not made by the subject. Reducing the vast possibilities to a narrow window of usable characteristics, including outsole dimensions and tread pattern, challenges even the best trackers. Without any information about the subject's footwear, interpreting tracks can be difficult.

LITERATURE REVIEW

A literature search was conducted in an attempt to locate any publications relevant to footwear (or lack thereof) worn by mispers. Search terms including combinations and variations or synonyms of missing person, footwear, reports, and comparisons in Google, Google Scholar, Google Books, JSTOR, Heinonline, ScienceDirect, PubMed, Semantic Scholar, and ResearchGate yielded no results on the topic. Related publications found in those resources discussed paradoxical undressing, color blindness, and tracking. Many studies also published experiment results related to visual working memory and object recall accuracy. Those experiments studied people's abilities to recall object shapes, positions and colors on a screen or in enclosed environments (Dave et al., 2021; Geißler et al., 2023; Hu & Jacobs, 2021; Sims et al., 2022); they were not conducted in field conditions where searches occur.

While there are plenty of manuscripts on footwear types (Hsu et al., 2008, p. 328), brands (Abbas et al., 2020), colors (Banerjee et al., 2014), and sizing (Sterling, n.d.; Zupko, 1977), none of them relate to missing persons. Bodziak's (2017, p. 208) observation "Most forensic case examinations involve athletic shoes…" was the closest to any footwear description of a specific population found in the review. No research on misper footwear descriptions was found, and likewise, no writings comparing reports of subject footwear with found descriptions were discovered. The value of this research is highlighted by the originality of this study.

METHODS

The intention of this research was collecting and analyzing foundational data to provide informational tools for searchers looking for clues including footwear and footprints to assist in finding a misper. If there was a fair likelihood that the misper traveled on foot at some point while missing, those incidents were included. By moving on foot, subjects leave tracks which are potential clues for searchers.

Retrospective data from missing person incidents were gathered by interviewing reporting parties, subjects' families, searchers, subjects, or reading media reports. Gathered data included footwear information from two stages of searches: (1) before the subject was found, and (2) after the subject was found. If details of the subject's alleged footwear were available before the subject was found, the recorded information included: type, color, brand, model, size, U.S. size classes (men, women, youth), and width. After the search concluded with a find, researchers then sought the same details about the subject's actual footwear (or lack thereof). When available, additional recorded information included the following: anonymized database number, source (searcher or media) code, unique case or mission number, jurisdiction/locality, state, country, FIPS code, date of search, Lost Person Behavior (LPB) category (Koester, 2008), footwear descriptive terms, alternative reports, additional comments, removal method and distance information for footwear found apart from the misper.

Exclusions

If a missing person unlikely traveled on foot while missing, they were excluded from this study. Examples of excluded searches consisted of movement other than on foot (e.g., airplane, wheeled transportation) or beyond the subject's control (e.g., abduction, entrapment, natural disasters, and water [flood, boating, drownings, etc.]). The screening excluded 15 searches with reported footwear information for reasons mentioned in the last sentence, and another 19 because the missing person remained at large on the date of submitting this paper. Although "search and rescue" is the common phrase, rescues that lacked a search component were excluded because two guiding principles for this research were subjects for whom a search was initiated and those who moved on foot. Due to the lack of documented footwear information, countless searches could not be included in this research.

Inclusions

Searches were filtered for organized search efforts for subjects who traveled on foot (e.g., hunters, hikers, despondents, children). All search subjects included in this research were located; none were still missing. One author (RS) assisted with search efforts for 273 (64%) of the incidents included in this study. Other searchers who participated in searches provided information for 100 (23%) of the incidents. Media reports with photos, video, or written descriptions accounted for 54 (13%) of the incidents.

RESULTS

An International Missing Person Footwear Database (IMPFD) was created to store research data. Footwear details of 428 missing persons incidents were catalogued based on observations of 413 search missions (13 incidents involved multiple subjects) from 1970 to 2024 (Figure 1). These searches occurred predominantly (81%) in Virginia, with most remaining cases in states depicted in Figure 2, and six searches (1.4%) from other countries. Collected data were stored in a Google Sheet. Python, R-studio, and the Plotly visualization library were used to create the graphics.

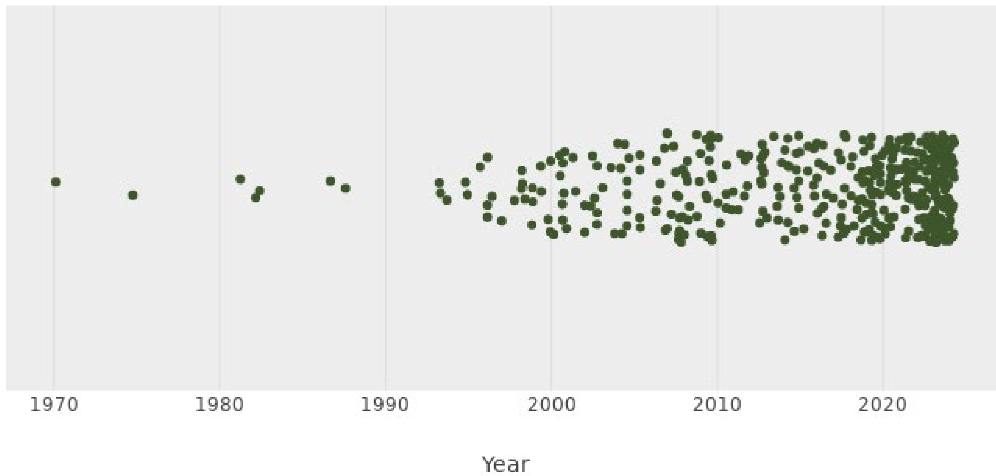

Figure 1. A Jittered Time Series Plot Showing Year of Each Case in the IMPFD

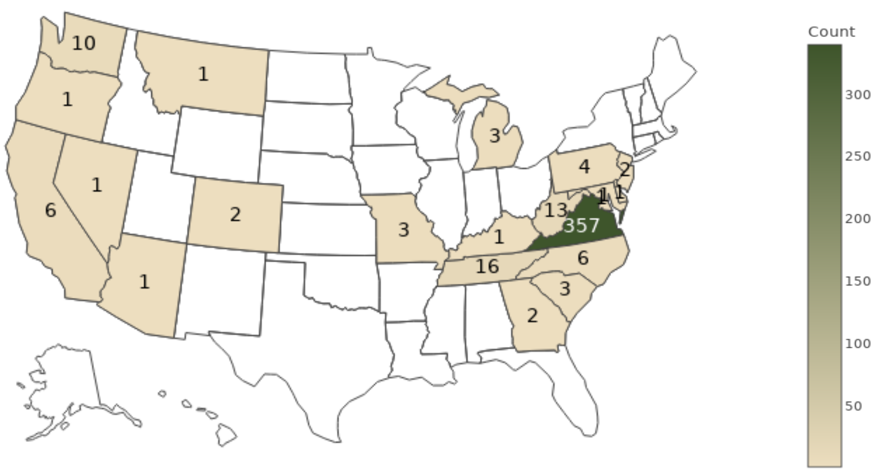

Figure 2. A Map of the U.S. Showing Quantities of Cases in the IMPFD

The observation unit (Ott & Longnecker, 2016, p. 26) of this retrospective research is an individual missing person. Outliers in individual occurrences include going missing more than once (four cases) and an individual exhibiting different footwear conditions between their two feet (11 cases). Data sorted into two categories originated from search mission briefings and/or interviews with family, friends, caretakers, or other reporting parties such as law enforcement officers. Though kept anonymous in the database, if any incidents involved a person that was the subject of multiple searches, each occurrence is considered individually and independently. The two categories used to segment the data, and overlap between the two, follow:

(1) Reports of footwear information before the subject was found

(2) Details of footwear (or lack thereof) donned by the subject when found
(3) Subjects for whom information was noted both before and after the person was found

“Reported” information included any details about the mispers’ footwear conveyed to searchers before the search ended. “Found” information presents details gathered about the mispers’ footwear after being found. Included cases contained 428 descriptions of footwear either before and/or after the subject was located. Research encountered footwear information reports for 347 (81%) incidents and examined footwear information for 265 (62%) subjects after being discovered (see Figure 3).

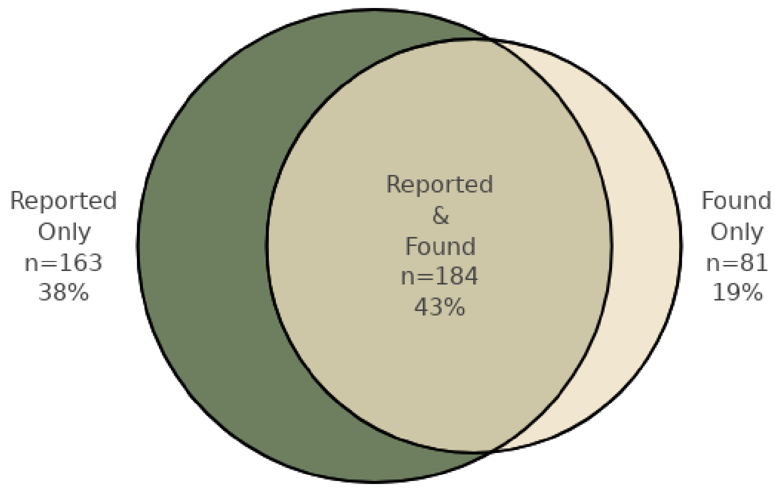

Figure 3. Venn Diagram Showing Numbers of Subjects and Report Types of Footwear Information

Data for reported and found details of the mispers’ footwear were divided into four main descriptive characteristics (type, color, brand, size). Type is the most general characteristic of missing persons’ footwear, and it can provide searchers with limited information. With additional data, it can be divided into additional categories or subcategories. Missing person footwear brands can assist trackers in narrowing the tread pattern possibilities to a few manageable options. Footwear colors can assist searchers in confirming clue assessment. The nominal size of a subject’s footwear can aid searchers in interpreting the dimensions of tracks. Figure 4 shows characteristic comparison quantities for reported, found, and overlapping (both) search phases. As an example of interpreting the frequency table in Figure 4, the bottom row shows that type, color, brand, and size were documented for both reports and found conditions (179, 99, 61, and 35 times, respectively).

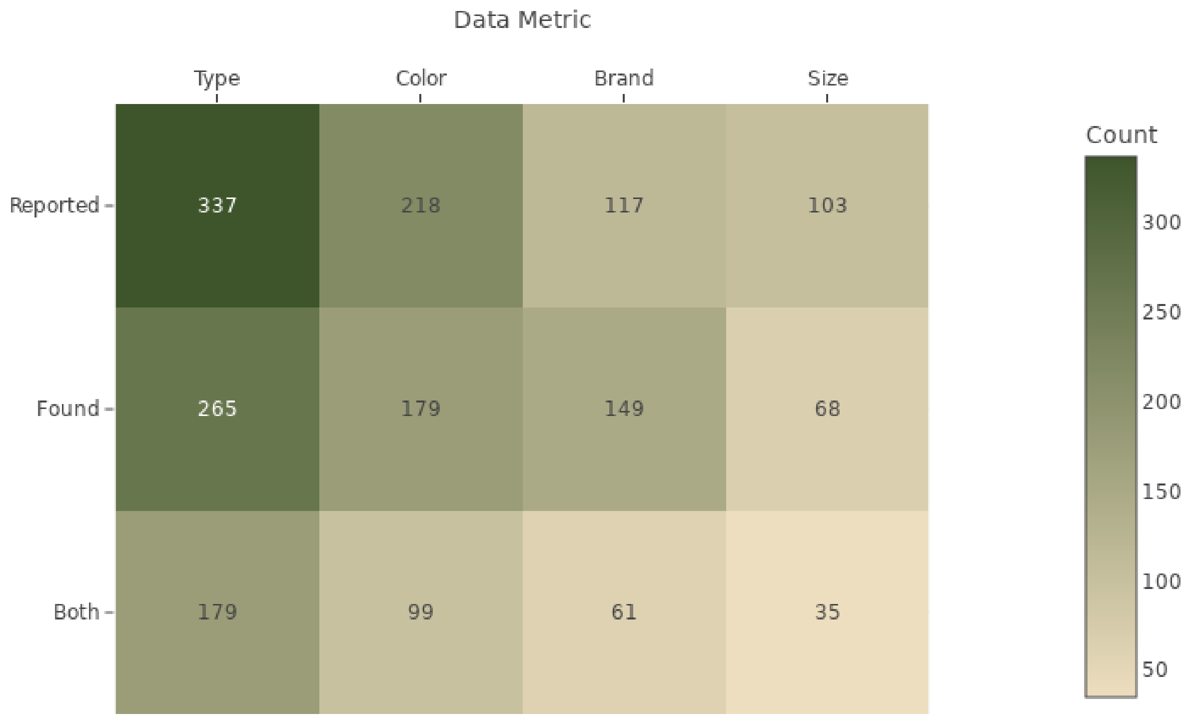

Figure 4. A Heatmap Showing Quantities of Documented and Comparable Footwear Characteristics

Footwear Types

The database organized footwear type into five categories: Boots, Shoes, Minimal shoes, Unshod, and Mixed. The first category defines boots as: "a fitted covering (as of leather or rubber) for the foot that usually reaches above the ankle" (Merriam-Webster, 2024). This paper adds a distinction to the "boot" definition: the top of the footwear is five or more centimeters above the ankle (e.g., hunting or hiking boots). The second database category defines shoes as footwear that typically stops at the ankle (e.g., tennis shoes, sneakers) and includes high-top sneakers. Next, the subcategory of minimal shoes includes open-toed or open-heeled shoes and shoes with outsoles measuring one centimeter or less compared to the insole length (e.g., flip flops, sandals). The unshod type describes subjects wearing just socks or those reported to be barefoot and/or found barefoot. If a person was reported or, more commonly, found wearing a combination of any two of the first four categories, they were designated as mixed.

Figure 5 shows percentages of footwear reports for 337 subjects and find types for 265 subjects. Subjects' reported and found footwear conditions included all five types. Shod subjects comprised the vast majority (93%) of reports, but fewer (70%) subjects were actually found shod on both feet. Footwear (or lack thereof) status observations at the conclusion of the search (265 subjects) noted 25% of them as unshod on both feet. Subjects found unshod represented several LPB categories, as shown in Table 1. Table 1 shows LPB category and quantities of subjects reported and found unshod; children and people with dementia were the most numerous. Eleven persons found with mixed footwear conditions included three that were reported mixed, and the other eight consisted of those found with different footwear on each foot or one foot shod and one unshod.

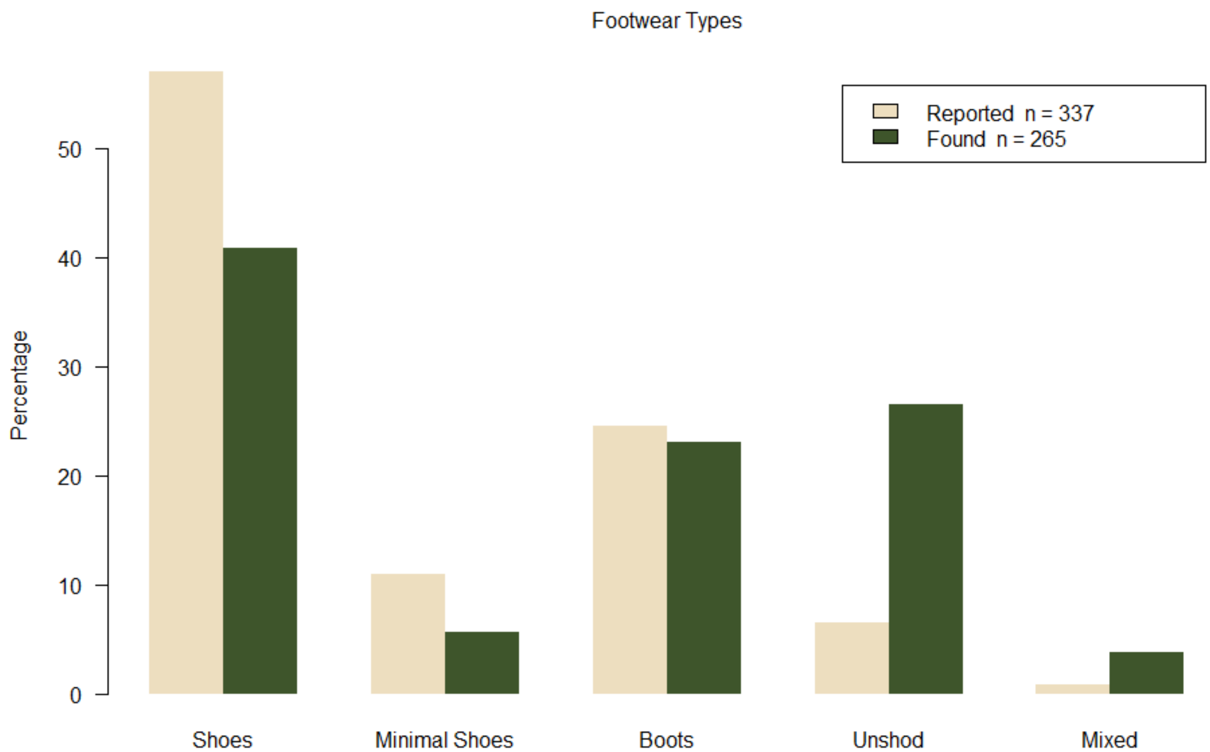

Figure 5. A Bar Chart Comparing Relative Proportions of Missing Persons Footwear Types

LPB Category	Reported (n = 24)	Found (n = 71)
Dementia	21%	28%
Despondent	8%	13%
Children (age 1 – 15)	46%	21%
Mental illness	4.2%	8.5%
Hiker	8.3%	11%
Autism	4.2%	7.0%
Abandoned Vehicle	4.2%	5.6%
Camper	--	1.4%
Substance Intoxication	--	4.2%
Unknown	4.2%	--
Total	**100%**	**100%**

Footwear Colors

Table 1. Lost Person Behavior Categories and Percentages of Subjects Reported or Found Unshod

Footwear reports involved color descriptions for 218 subjects, or 63% of footwear reports. Of those reports, 20% were for boots, 77% for shoes, and 3% for subjects with mixed types. Found footwear accounts included color for 78% of 187 subjects found shod with the same footwear on both feet. Colors were noted for 12 items of footwear worn by ten individuals with mixed footwear conditions; one mispers wore two different colors of footwear, and another was found wearing two different brands of white shoes. As a result of finding footwear separated from the subject, colors were determined for footwear of 22 subjects found with both feet unshod. Figure 6 shows the more common quantities of footwear colors distinguished by reported and found shoes and boots. The six colors reported only once, and the five colors found only once, were omitted from Figure 6.

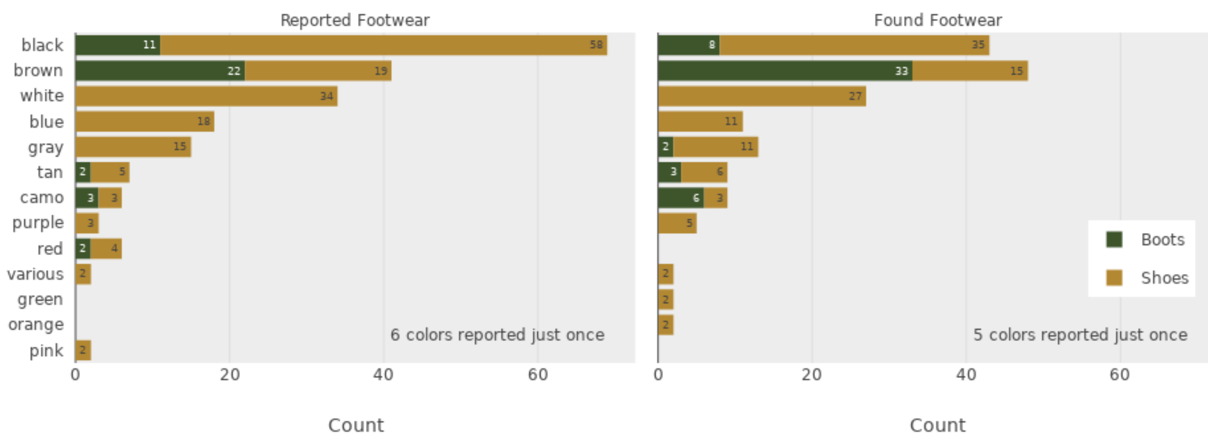

Figure 6. Common Color Quantities of Two Types of Reported and Found Footwear

Footwear Brands

Footwear descriptions included brand names for 117 subjects or 34% of footwear reports. Found footwear accounts included brand determinations for 64% of 188 subjects found shod by the same footwear on both feet. Brands were determined for ten items of footwear worn by eight individuals with mixed footwear conditions; two mispers wore two different brands of footwear. As a result of finding separated footwear during the search, brands were determined for 30% of subjects found unshod on both feet.

Figure 7 shows breakdowns of brands by type (shoe vs. boot) and search phase (report or found). Individual reports or finds – 11 brands reported only once, and 27 brands found only once – were omitted from Figure 7. Shoes comprised a majority (78%) of footwear brand reports. Nike was the most commonly reported shoe brand, followed by Crocs. Boots comprised a minority (21%) of footwear brand reports. Five brands were reported twice each, with an additional 15 brands being reported only once. Brahma, Rocky, and Timberland tied for the most commonly found boot brands on three subjects (11%) each.

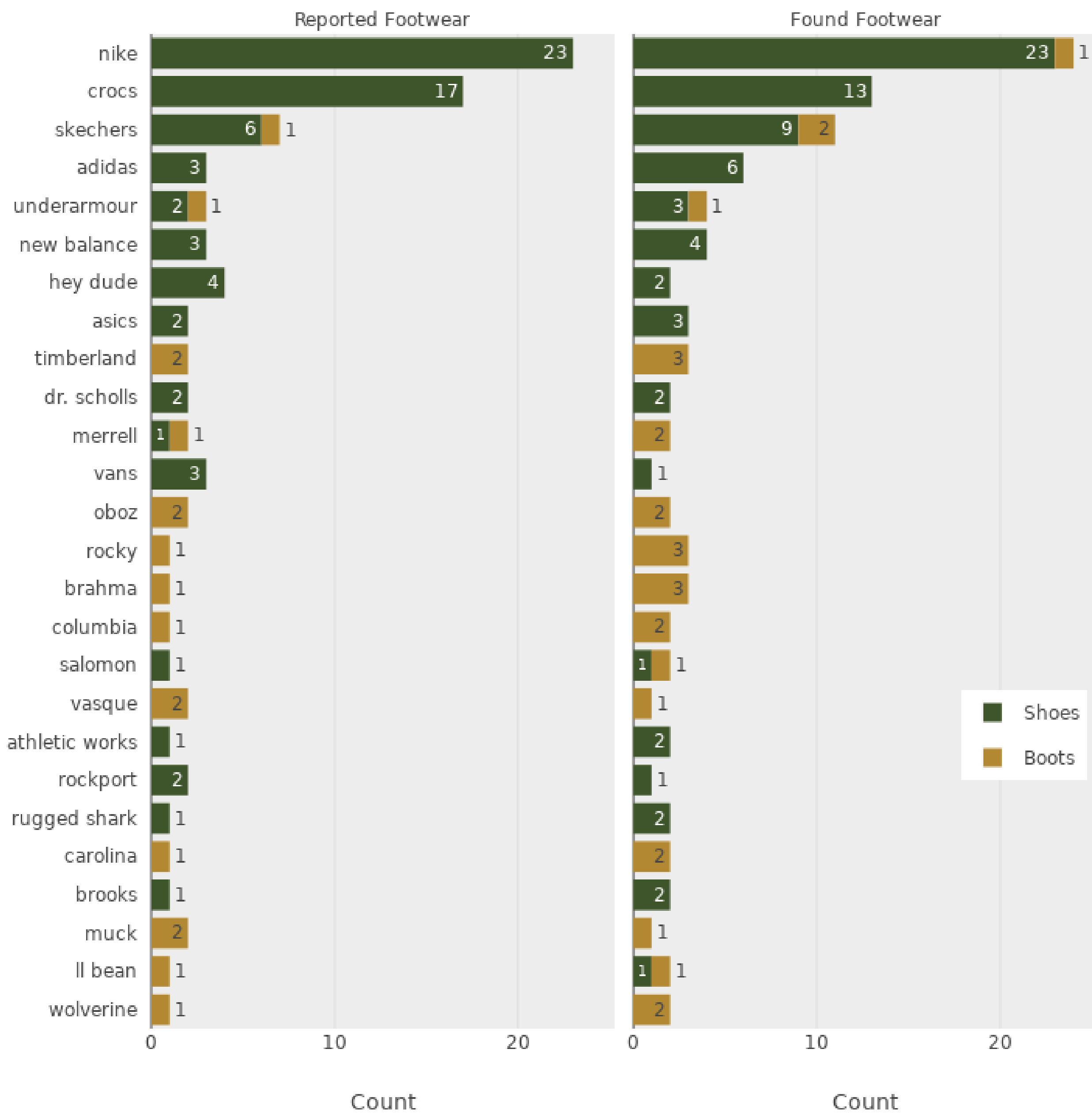

Figure 7. Chart Showing the More Commonly Reported and Found Footwear Brands

Nominal Sizes

The nominal size of footwear was the characteristic least reported (30% of 347) and least noted when found (26% of 265). Reported sizes ranged from youth 2½ to men's 15, and found sizes from youth 2 to men's 14. Of subjects' whose size was noted, 88% of reports and 71% of found footwear descriptions included additional U.S. size qualifiers (e.g., men's, women's, youth). Figures 8a and 8b show reported and found footwear sizes by gender and footwear type.

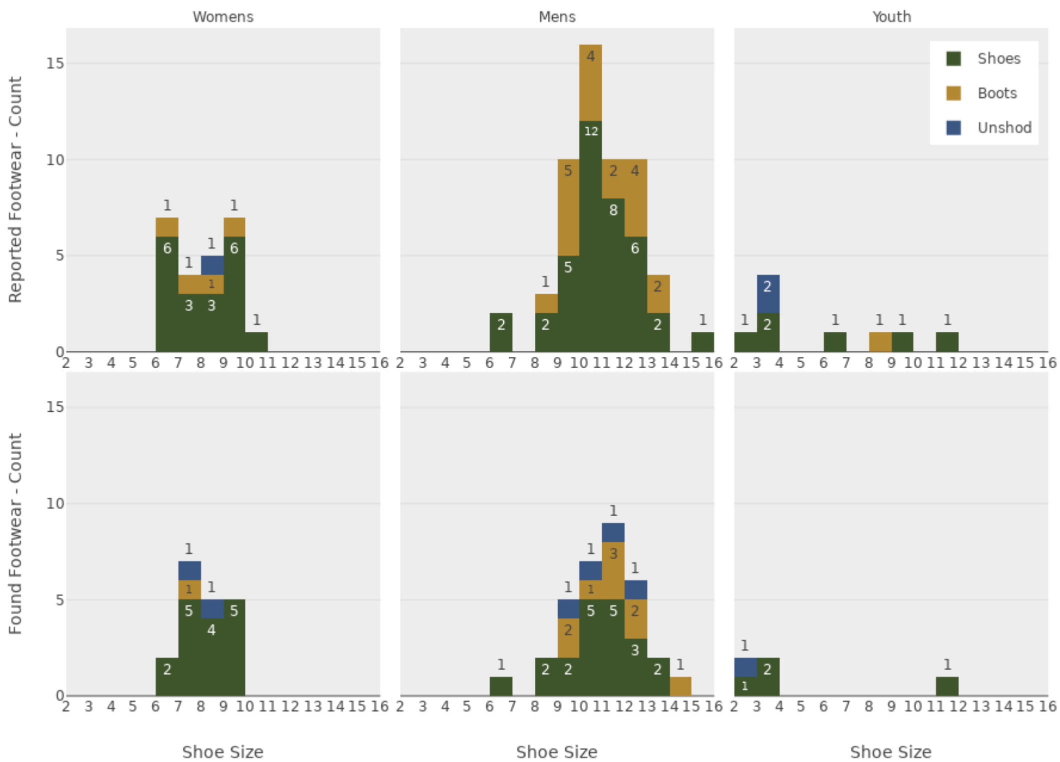

Figure 8a. Chart Showing Quantities of U.S. Sizes Reported and Found as Arranged by Gender

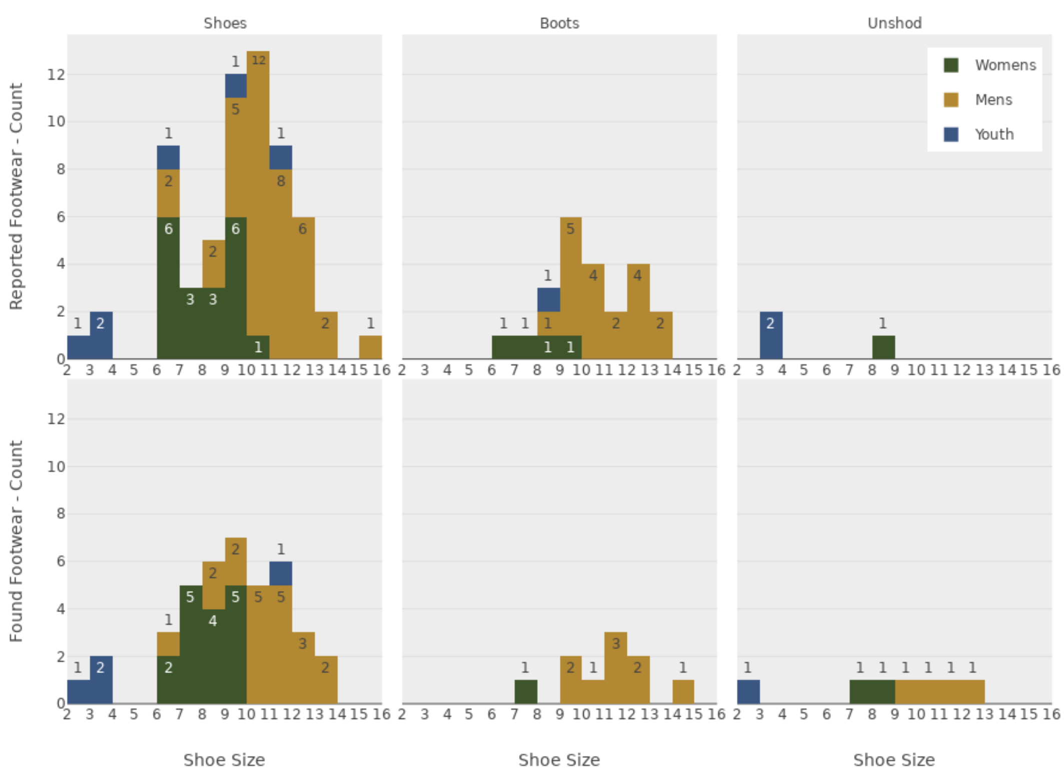

Figure 8b. Chart Showing Quantities of U.S. Sizes Reported and Found as Arranged by Type

DISCUSSION

Conducting this research highlighted the difficulty in obtaining footwear information. From this study, a complete lack of any footwear information excluded hundreds of searches in which only the authors assisted, not to mention thousands of other searches that were conducted without documenting accessible footwear information.

The lack of reported footwear information is not due to an absence of prompting, since many missing person questionnaires exist in books (Diaz & McCann, 2013; Hurth, 2012; Koester, 2008; NASAR, 2018; Osuna, 2021, 2021; Robbins, 1977; Speiden, 2009, 2018; Stoffel & Stoffel, 2017; Taylor & Cooper, 1990, 2014; Young, 2021), and websites (EMSA, 2010; KYEM, 2022; NCMEC, 2022; NEWSAR, n.d.; UCSO, 2014). These questionnaires include reminders to document some description of footwear – typically including style, color, and size – reportedly worn by subjects. Questionnaires lacking a prompt for footwear information are rare, are typically brief, and lack many other questions (VSP, 2006). Even when most forms contain footwear prompts, several factors prevent the collection of footwear information. In the urgency of a missing person situation, footwear questions are likely discounted or ignored. While nearly all (97%) footwear reports contained information about the footwear type, fewer contained color (63%), brand (34%), or size (30%) information that is helpful while investigating clues such as footwear or associated track pattern and dimension information.

Footwear seems to be the least reported clothing item in missing person reports. A crude survey of 67 announcements found descriptions given for the head, torso, legs, and feet of missing persons in 88%, 64%, 64%, and 49%, respectively. Because an observer more readily notices clothing that is relatively larger in size and visible within their own eye level, a subject's top-wear (e.g., shirt or coat) tends to be reported more frequently than the lower-wear (e.g., pants or shorts), and footwear is reported the least. Nonetheless, footwear descriptions remain imperative to improving trackers' informed assessments. To provide trackers with pertinent information, it is recommended that more effort be given to investigating footwear descriptions.

Figure 9 is a representation of the reliability of reports. It shows quantities and percentages of reported footwear characteristics that were correct or incorrect. These results were determined by comparing information for subjects for whom both reported and found information was catalogued (see Figure 4, bottom row). An example of reading the figure is that reported and found brands were both noted for 61 persons, and 53 (86.9%) of those found were consistent with the reported brand.

Since having accurate information assists trackers in assessing tracks and other clues, it is important to know the reliability of reported information. The hashed regions represent cases where footwear type was reported, and though the subject was found unshod, their footwear was found separate of them and compared to the reported type information. Trackers may be interested in that information because subjects who become separated from their footwear likely left shod and unshod tracks. The type rows suggest that type was reported and noted when found for 198 subjects, 140 (70.7%) of whom were wearing the reported type of footwear. An additional 16 (8.1%) subjects were found unshod, but footwear found separate of them during the search was consistent with the reports. Footwear descriptions, even if found separate from the subjects, are significant since there are likely to be tracks made when the subject was wearing the footwear; those tracks could lead to the subject.

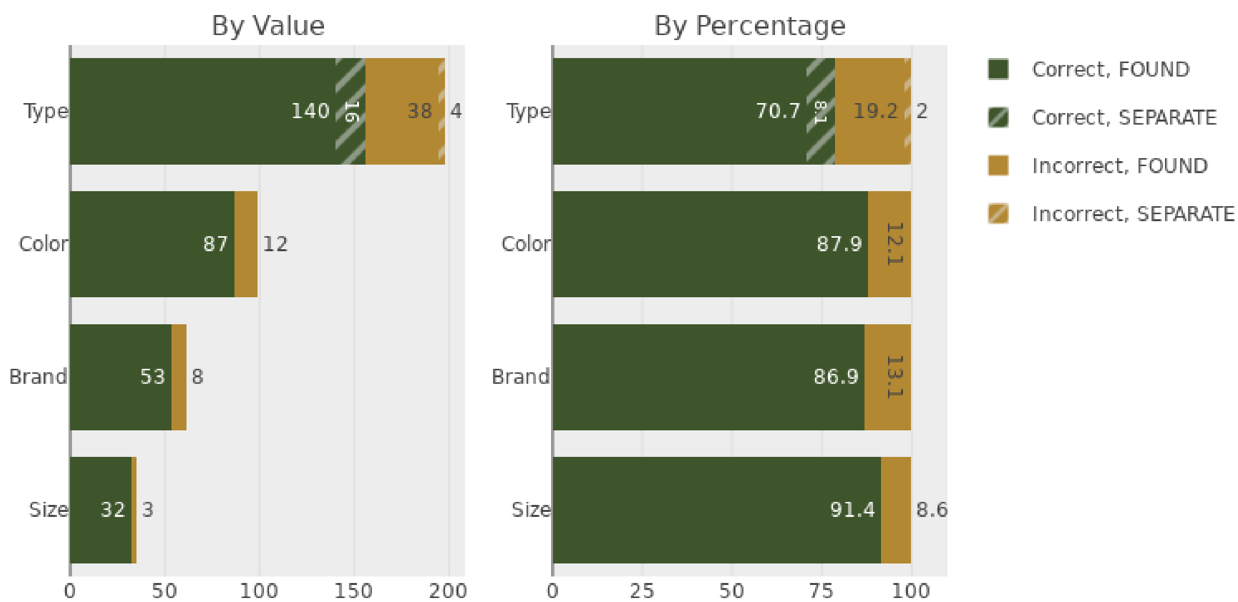

Figure 9. Two Charts Comparing Counts and Percentages of Reports Compared to Found Characteristics for Footwear Type, Color, Brand, and Size

Comparing Types

Results showed footwear type (shoe, minimal shoe, boot, unshod, and mixed) as the most common selected characteristic described in both reported and found footwear accounts. Type information was available for 79% of all subjects, and for 97% of cases with some reported footwear information. Found footwear information included type for 61% of all cases and 99.6% of cases in which any information about the subject's footwear was documented. Of the 265 subjects for whom their found footwear type was documented (Figure 4), 42% were wearing shoes, an additional 6% were wearing minimal shoes, 23% were wearing boots, 25% were found unshod, and 4% were found mixed. Some footwear styles notably absent from the database included novelty shoes and women's dress shoes (e.g., high heels and wedges).

Figure 10 is a heatmap comparison of the data points in the "Both" row of the "Type" column of Figure 4 which shows a value of 179. An example of reading a row in Figure 10 uses the "Minimal" row, indicating that 1 + 10 + 0 + 1 + 7 = 19 subjects were reported to be wearing the footwear type minimal shoes. Of those 19, one (5.3%) subject was found wearing boots; ten (53%) were found wearing minimal shoes on both feet; one (5.3%) were wearing shoes; and seven (37%) were found unshod. The minimal shoe report subcategory exhibits the highest percentage (47%) of subjects reported to be shod who were then found unshod. While not enough for rigorous statistical analysis, the data suggests a pattern that occurs frequently enough to factor into anticipation of tracks, sign, and clues left by the subject. The trend of minimal shoes being shed more frequently than other footwear types is reflected in the discrepancy between reported and found percentages of minimal shoes, as well as the related discrepancy between the percentages of subjects who were reported to be unshod and those found unshod. While the difference in minimal shoe percentage change does not account for the entire change in the unshod category, the change in shoe percentages does explain the unshod discrepancy, and the percentage discrepancy in the mixed category, as well. Interestingly, of the 19 subjects reportedly wearing minimal shoes, none of them were found with mixed footwear conditions. One explanation for that occurrence is just a lack of a significant amount of data.

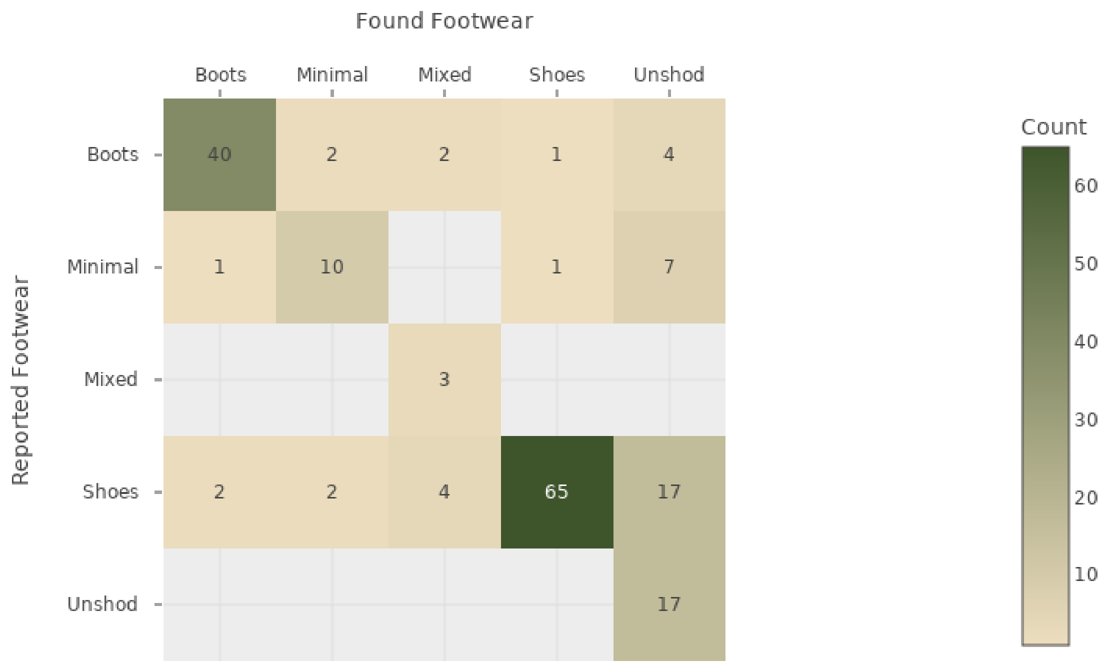

Figure 10. A Heatmap Comparing Reports with Found Footwear Types

The majority of subjects shown as found with their reported types of footwear or lack thereof (e.g., boots 82%, minimal 53%, mixed 100%, shoes 72%, and unshod 100%) is consistently shown across all five types as the darkest cell for each row in the Figure 10 Heatmap. The mixed and unshod proportions will likely decrease with additional data. Ironically, two subjects reported to be unshod did, in fact, wear footwear at some point while missing; their footwear was found removed, and nearby the subjects.

Found Unshod

While most (71%) searches involved subjects found shod, searchers found a significant portion (25%) of subjects unshod and more partially unshod. Subjects found unshod presented as either barefoot (66%), wore thin fabric such as socks or stockings (23%), had one sock and one bare foot (3%), or unknown (8%). Searchers found 50 items of footwear belonging to 26 unshod subjects. While a few subjects found with mixed results were shod with different footwear, most (73%) were shod on one foot and unshod on the other. Only 10% of subjects reported to be wearing boots were found unshod, while 19% of those reported to be wearing shoes were found unshod.

The shod category that was found unshod the most was subjects reported to be wearing minimal shoes (37%). The difference in the latter is likely due to the lack of structure in the footwear to keep them on the feet in various environmental conditions. Type reports (unshod, minimal, shoes, boots, mixed) resulting in subjects found unshod tabulated as 100%, 45%, 21%, 8.3%, and 0% of subjects, respectively. Interestingly, none of the 24 cases in which subjects reported to be unshod were found wearing footwear. Two of them, however, wore footwear while missing, but their footwear was removed and found separately during both searches. Speiden (2009, p. 104, 2018, p. 120) describes these occurrences, “Remember - even if there is accurate information about the subject’s footwear, it is quite possible that the subject may have lost his/her footwear…” This phenomenon is also mentioned in another tracking book (Moreira, 2016). If those cases stand out in someone’s memory more so than typical cases of shod subjects, shod versus unshod subject data may be skewed towards a higher-than-actual percentage of subjects found unshod (less common).

Researchers noted various reasons for 71 subjects found with one or both feet unshod: voluntary removal (20%); starting unshod (25%); paradoxical undressing (5.6%); involuntary removal (e.g., stripped by mud, vegetation, or water – 15%); medical circumstances, medication, or drugs involved (2.8%); and undetermined (31%) – though 25% of the ‘undetermined’ subjects likely started out unshod.

Paradoxical undressing (PU) is a terminal behavior associated with lethal hypothermia (Wedin et al, 1979). Anecdotes describe the actual oldest cases of PU encountered (Brown, 2009; James, 1965). Dr. Vejlens’ (1952) and subsequent papers reported over 200 cases of pre-terminal disrobing behavior (Albiin & Eriksson, 1984; Brändström et al., 2012; Gormsen, 1972; Hirvonen & Huttunen, 1982; Hleșcu et al., 2022; Kinzinger et al., 1991; Krispin et al., 2011; Lim & Duflou, 2008; Mizukami et al., 1999; Rothschild & Schneider, 1995; Shimizu et al., 1996; Sivaloganathan, 1985, 1986; Wedin et al., 1979). Though several theories about the cause of PU persist, none have been proven (Mizukami et al., 1999).

Researchers discovered 18 subjects for whom searchers found their footwear at different distances: less than six meters (56%), six to 100 meters (22%), and over 100 meters (22% - see Figure 11). These distances reflect more travel distance than mere victims of paradoxical undressing. Research encountered 55 cases of paradoxical undressing in literature. That research described distances of footwear from the subject at zero to six meters (74%), six to 100 meters (24%), and greater than 100 meters (2%) (Albiin &

Eriksson, 1984; Bertil Wedin et al., 1979; Gormsen, 1972; Sivaloganathan, 1986; Vejlens, 1952, as cited in Gormsen, 1972).

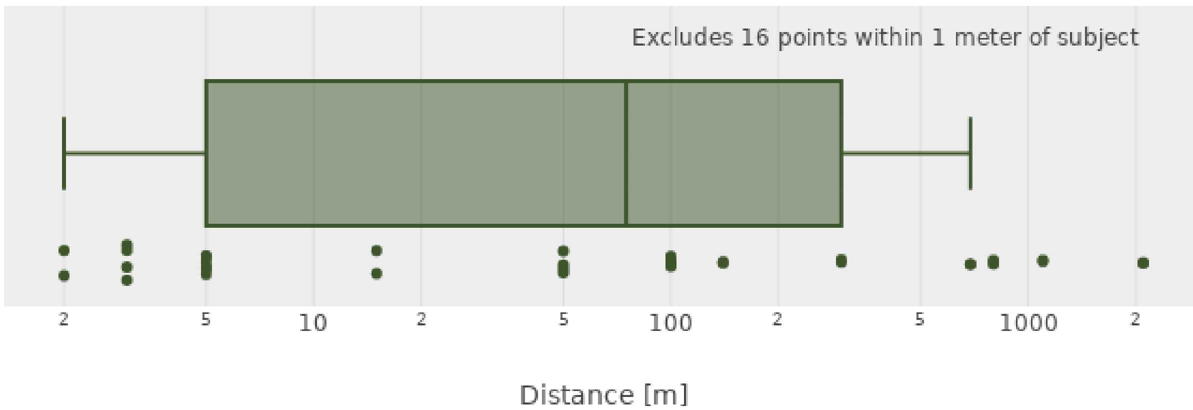

Figure 11. Boxplot Showing Distances, on a Log Scale, of Footwear Found Separate of Missing Persons

Comparing Colors

Knowing the subject's footwear color is of interest to searchers for a couple of reasons. First, footwear color, alongside other design characteristics, can assist trackers working to discover a tread pattern via research of a particular brand, model, and version of footwear. Second, color confirmation increases the confidence and ability of searchers to validate whether an item found during the search belongs to the subject. Other factors, such as the appearance of how a found item of footwear has been in its location and the size of the footwear, should be considered when assessing the relevance of any potential footwear clue.

Table 2 shows percentages of interactions between reported and found colors. Any sample sizes (n) with a ".5" value reflects an individual for whom information was noted for only one item of footwear; whereas individuals with both items of footwear were counted as "1". Color information existed for 63% of subject reports and 56% of found subjects. Black and white comprised the most commonly found shoe colors (28% and 23%, respectively). Brown, the most common boot color, equaled or surpassed all other reported (50%) and found (62%) boot color quantities combined. While it would be interesting to compare percentages of colors of shoes worn by subjects to those of a country's population, the only reference to general footwear color choices differed from our findings and was discovered in Kuru's (2022) online reference to footwear colors. In general, "Americans' top two most popular footwear colors are black (44%) and white (17%)." The difference between the two samples is likely to be inherent in the discrepancy of vast quantities of people buying footwear versus only hundreds of cases in this research. When comparing footwear color reports with found information, shod subjects showed the vast majority (88%) as correct and only 12% as incorrect (Figure 9). All discrepancies between color reports and finds occurred with shoes.

Color	Report	Found	Found Equals Report	Found Differs From Report	Report But No Found Info	Found But No Report
n	**217**	**152**	**86.5**	**11.5**	**120**	**66**
Black	31.3%	23.4%	21.1%	8.7%	40.8%	26.5%
Brown	18.2%	26%	25.1%	17.4%	13.3%	26.5%
White	15.7%	15.8%	10.5%	17.4%	19.2%	21.2%
Blue	8.5%	6.9%	11.1%	8.7%	6.7%	–
Camo	2.8%	5.9%	7%	–	–	4.5%
Gray	6.9%	5.9%	7%	21.7%	5.4%	3%
Tan	3.2%	5.3%	4.7%	17.4%	0.8%	6.1%
Purple	1.4%	2.6%	2.3%	–	0.8%	1.5%
Pink	0.9%	–	–	–	1.7%	–
Red	2.8%	1.3%	–	–	3.3%	–
Green	0.5%	0.7%	–	–	0.8%	1.5%
Teal	0.5%	–	–	–	0.8%	–
Orange	–	1.3%	–	–	–	3%
Peach	–	0.7%	–	–	–	1.5%
Two +	7.7%	4.3%	8.8%	8.7%	6.3%	4.5%
TOTAL	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 2. Frequency Table Showing Comparison of Footwear Color Reports with Found Information

Overall, color reports are reasonably accurate when compared with found footwear. This is helpful to paint a previously-unavailable picture of reliability in reported characteristics. Less common shoe colors may increase confidence in relevance assessment due to the reduced frequency of those found with missing persons. Reported-to-found-color errors were mostly (7 of 12) color discrepancies (e.g., reported brown but found blue), and the remaining five were value discrepancies (reported brown but found tan).

Comparing Brands

Determining information about the brand of the subject's footwear provides a significant step towards determining their outsole pattern. After learning of the subject's reported footwear brand, and with knowledge of common brand tread patterns, some trackers have recognized the missing person's tracks. Awareness of other footwear information such as model, color, and size can help deduce a subject's tread pattern and dimensions. If someone at the search is wearing footwear similar to that which the subject is reported to be wearing (or the subject has an older pair of the same brand and model in their closet), that can be helpful for trackers. In the absence of a footwear report, requesting the subject's family provide a picture of subject wearing footwear, a related shoebox, or a receipt from an online retailer would be helpful. In addition to color and size, these characteristics help narrow possibilities of what tracks to seek.

Footwear brand reports existed for 37% of all subjects reported shod and for 68% of subjects found shod. Interestingly, Figure 4 shows that the brand category is the only characteristic for which the quantity of found records exceeded that of reported records. The figure also shows that both reported and found brand information existed for 61 (14% of all) subjects. Comparing reported brands with found brands resulted in an 87% success rate – the second highest correct rate of compared variables (Figure 9). This finding suggests that if a reporting party is able to recall a footwear brand, those reports are quite accurate.

Brand-specific inferences from the IMPFD are described here. Nike, which claims over 50% of the U.S. shoe market (Goddiess, 2022) and 38% of the worldwide footwear market (Andersen, 2023), dominated the found shoe brands. They were worn by 38% of the 61 subjects for which research determined shoe brand. Boot brands, however, proved more diverse. No brand was found on more than three subjects. Three subjects wore steel/composite-toed boots; this footwear may be worth researching to determine if there is any difference in track dimensions compared to regular boots.

Figure 12. *Images of a Crocs™ Shoe and Similar Shoes Showing Similar and Dissimilar Tread Patterns*

As a last learning point from the brand data, there is a significant discrepancy between the number of subjects reported to be wearing Crocs, and those actually found wearing Crocs. Crocs is the only brand with more than 4 counts in the reported and found brand quantities that also had a value of reported subjects which exceeded the number of subjects found actually wearing Crocs. Crocs was one of three brands that had two occurrences of shoes being found separate of the subject. Nike had more with five of 23. Of the 17 subjects reported to be wearing Crocs, eight were found wearing Crocs; no footwear type or brand was determined for eight; and one was wearing Rugged Shark shoes, a brand similar to Crocs. Exemplified by the last case, likelihood for the higher reports of Crocs is that there are shoes that look similar to Crocs but are made by other manufacturers. Figure 12 shows the outsole of a common Crocs pattern. To the right of that shoe are other shoes with similarly-structured uppers, and similar (tan shoe) as well as dissimilar tread patterns (blue and green shoes). A Sperry-Margaritaville pairing of loafers is another combination of shoes that may have similar uppers but they have a distinctly different tread pattern.

Comparing Sizes

Footwear "size" can be interpreted two ways that are loosely related. Firstly, the nominal size of footwear is a description given by the manufacturer. Secondly, size can be interpreted as length, width, or other dimensions of certain features. Knowledge of a subject's footwear size can provide trackers with an approximate idea of resulting track dimensions. While there is good information for SAR trackers regarding footwear sizes, nominal size systems are varied and can be complex.

The U.S. sizes in the IMPFD do not characterize dimensions of tracks because they are catalogued in three classes (youth's, men's, and women's), which have different dimensions for a given size in each of those three classes. Bodziak (2017, p. 189) describes the lack of consistency across the footwear industry: "there are standards in shoe sizing, but there is not standardization between manufacturers." Some individual manufacturers do, however, provide size charts with measurement data (Andersen, 2023; Crocs.com, 2024; Rockyboots.com, 2024; RunRepeat, 2024). The nominal size, therefore, can give a good indication of the length of the outsole, as can the track length made by the subjects' bare or shod feet, even if a searcher compares the reported size to be smaller, similar, or bigger than their own footwear. With the variety of shoe sizing systems in the world, it will likely be necessary, or at least convenient, to convert sizes in the IMPFD to a more standard system such as the European or Mondopoint system for ease of comparison and dimension relationships.

Size information proved to be the rarest characteristic noted when found, and thereby provided the fewest cases (35) for comparison (Figure 4). Size information filtered for both reported and found yielded eight cases for boots, 26 for shoes, and one un-typed. Shoe sizes seem more accessible than boot sizes because size is typically printed on shoe tongues. Most boots need to be removed from the person to observe the nominal size, presenting an obstacle to data collection. Some footwear have the size stamped in the outsole design (see Figure 12).

A half-size margin of error was used as consideration for correct/incorrect assessments. If the report stated size 8, and the subject wore size 7½, 8, or 8½, the comparison was counted as correct. If the same subject wore footwear sized size 7 or smaller, or size 9 or larger, the comparison was tabulated as incorrect. Figure 13 shows found sizes compared to reported sizes. Find information showed 91% of the size reports (88% of boots and 92% of shoes) as correct. Size provided the lowest quantity for comparison and the highest success rate among the four characteristics (Figure 9).

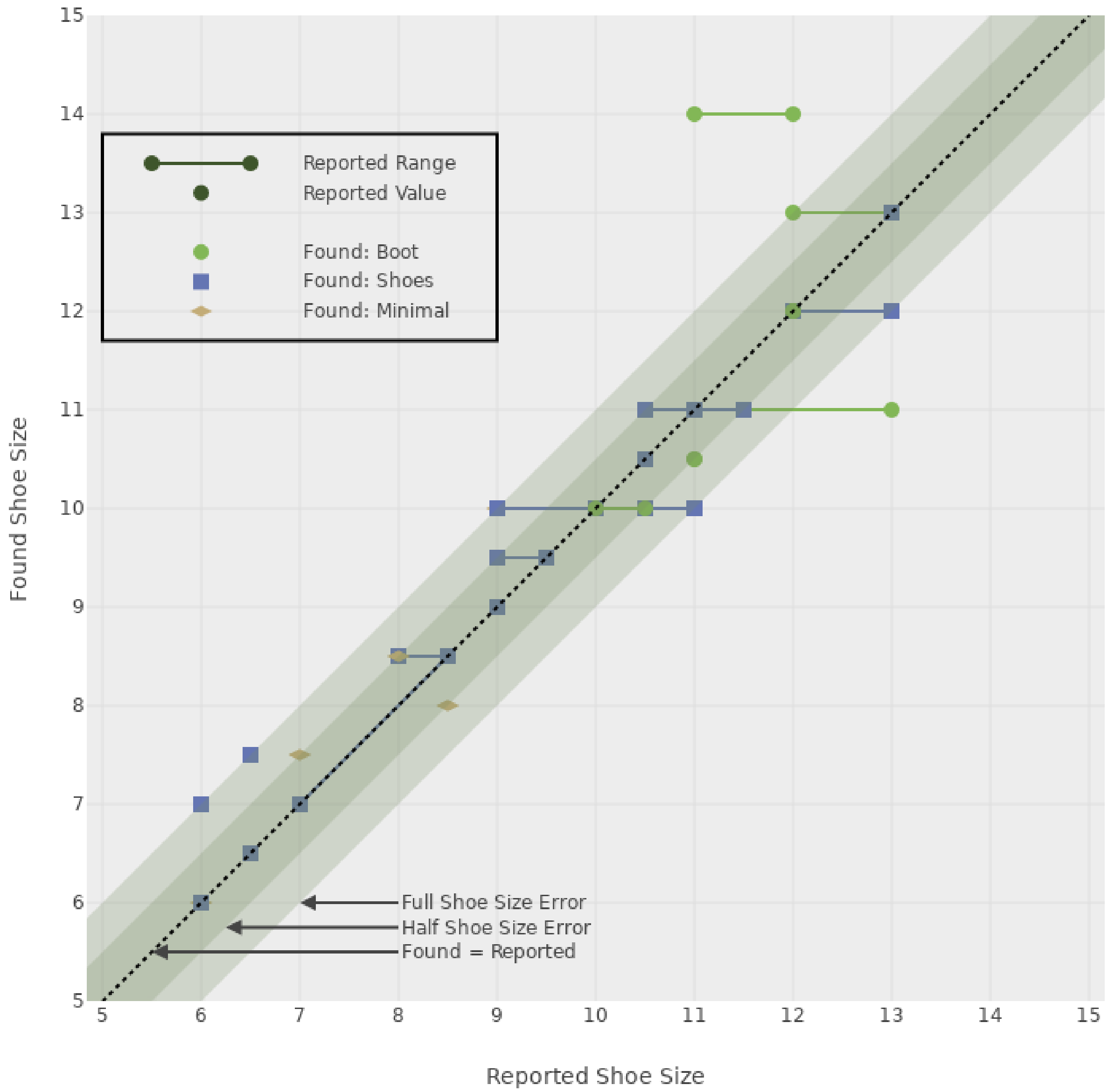

Figure 13. Regression Plot Comparing Found with Reported Footwear U.S. Sizes

Recommended Footwear Form

The research was unable to locate questionnaires or other documentation designed to record information about subjects' footwear when found. With the interest in contributing to the data already collected, this paper presents Figure 14, two sides of a card designed to assist with footwear information documentation before and after the subject is found. While non-trackers can complete the footwear information queried in most lost person questionnaires, a trained visual tracker should collect the information on this card for these reasons: (1) a tracker should be familiar with the terminology, (2) a tracker should be practiced in footwear measurement techniques, and (3) a tracker will be better trained to utilize this information.

Date / Time________________________________

Mission #_________________________________

SUBJECT REPORTEDLY WEARING

Type (Shoe, Boot) _______________________

Brand / Model ___________________________

Color(s) ________________________________

Size _______________

Circle if known (Men's • Women's • Child/Youth)

NOTES: [e.g., Date & Place of Purchase, Description (material, laces, velcro) Tread Pattern, Alternate Footwear, Older Pair Available?]

SUBJECT FOUND WEARING

Brand_____________

Color_____________

Type_____________

Size_____________

Circle if known (Men's • Women's • Child/Youth)

Interviewer______________________________

Images with scale available? (Y/N)___________

Known Footwear (1)

Color(s)_____________

Brand_____________

Insole Length_____________

Outsole Length_____________

Outsole Width_____________

Heel Width_____________

Size_____________

Circle if known (Men's • Women's • Child/Youth)

Known Footwear (2)

Color(s)_____________

Brand_____________

Insole Length_____________

Outsole Length_____________

Outsole Width_____________

Heel Width_____________

Size_____________

Circle if known (Men's • Women's • Child/Youth)

Figure 14. Footwear Information Card Recommended for Tracking Resources and Inclusion in Missing Person Questionnaires

CASE STUDY

A hunter, missing in Mecklenburg County, Virginia in December 2021 was initially reported to be wearing camouflage boots. A tracker interviewed the misper's family, and they located a box that described the boots likely worn by the misper (Figure 15A). With brand and size information, internet research produced the suspected footwear's tread pattern and measurements (Figure 15B). The tracker initially found a set of tracks that, while similar to the suspected tread pattern, was actually different in both characteristics and dimensions (Figure 15C). The tracker later found a track consistent with the suspected misper's footwear (Figure 15D). Shortly thereafter, the misper was found nearby the track, over a kilometer away from the point last seen, wearing the suspected boots (Figure 15E).

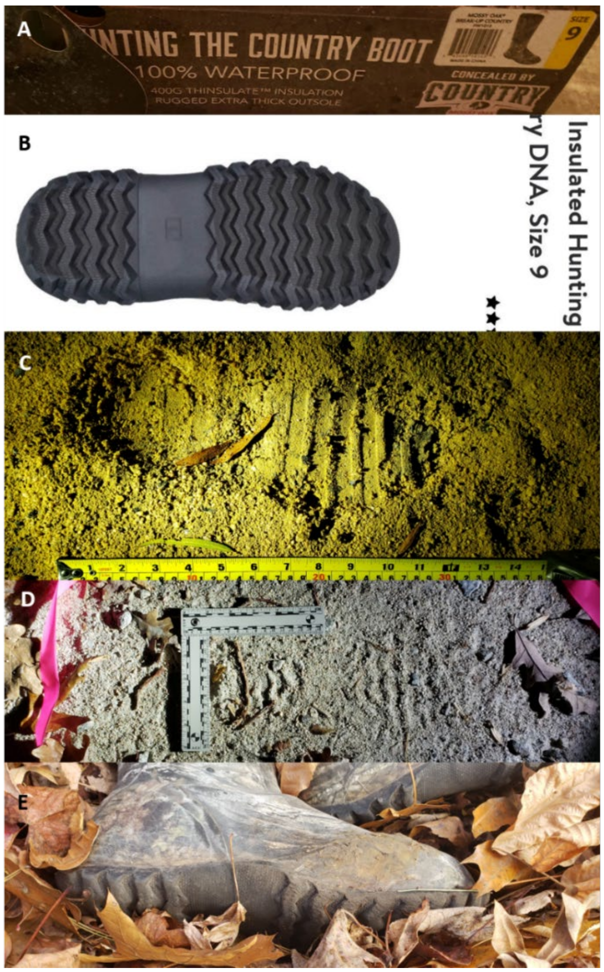

Figure 15. Images of (A) Box of Likely Footwear, (B) Boot Outsole from Walmart App, (C) Dismissed Track, (D) Suspected Track, and (E) Misper's Boot Outsole

LIMITATIONS

Many comparisons discussed in this paper represented statistically small sample sizes. No form or document was found that collects found footwear information. Hopefully that absence will be alleviated by the form presented in this paper. More data may prove out or modify noted trends in footwear characteristics involved in searches. An author (RS) participated in the search efforts for 64% of the subjects included in this study, increasing potential for some bias in the information. With the expansion of the IMPFD, gathering more search data may reduce that percentage and potential biases. Access to relatives, friends, caretakers, or acquaintances who are aware of subject footwear information is crucial; a lack thereof results in data omissions.

ADDITIONAL RESEARCH

One intention of creating the IMPFD was to provide foundational data for numerous subsequent studies. Further studies recommendations include gathering more data similar to this study to increase the database. Gathering enough data to compare the effect of climate (or latitude) on misper footwear findings, or an urban-rural comparison of the same, could be helpful.

Due to the lack of data on basic interpretations (e.g., made by subject or not) of tracks found at searches, research could be conducted to gather and report that information. Moreover, the authors recommend a study of additional clues found during searches for missing persons, particularly those that were confirmed to have been made by or belonging to the missing person. The potential exists for future studies to utilize some of this paper's findings to generate heuristics for predicting clue and track search image information. The catalogued brands and sizes of footwear will provide guidance for additional research into footwear and track dimension relationships. For example, a study can be conducted to determine if composite-toed boots have measurably different outsole dimensions when compared to those of similarly-sized regular boots.

CONCLUSIONS

People in the United States purchased over two billion pairs of shoes each year from 2010 through 2019 (Statista, 2024). Even though an extremely small portion (approximately 0.2%) of the entire U.S. population is reported missing each year, narrowing down the possibilities of footwear worn by a particular subject to useable characteristics, including the tread pattern and dimensions, remains a daunting task for even the best visual trackers.

Trackers want to find and follow tracks left by subjects. In the absence of any information about the subject's footwear, difficulties exist while sorting out the subject's tracks from those of anyone else walking around, including searchers. Having some information about the footwear helps narrow down possible tracks by a process of elimination. Even if searchers have a thorough report of the subject's footwear, the subject can, at any time, lose or remove their footwear and continue moving unshod. In those cases, knowing the nominal size of the subject's footwear - or better yet, having access to footwear for measurements – can provide useful information to distinguish subject's tracks from tracks of others.

This study focused on developing a database of information that could help interpret tracks potentially left by a mispers. While the color and brand name of the shoe have little to do with track dimensions, those characteristics can assist in determining track patterns, and they also give information about what clues search teams seek. Together, these data may assist in finding the subject.

All data in this research was collected from resolved missing person cases. A significant majority (80% - 91%) of the footwear reports collected in this study turned out to be correct, as confirmed when the subject and/or their footwear was located. Searchers found twice as many subjects wearing shoes (50%) than boots (25%), and they found a significant portion of subjects partially or completely unshod (25%). Searchers found the majority (56%) of unshod subjects' footwear within sight (less than six meters) of the subject, and they found 22% of subjects' footwear within 100 meters of the subject.

Subjects typically wore black (29%) or white (30%) shoes, and subjects wore brown boots most (62%) of the time. While variety exists in the types and characteristics of footwear missing persons wear, the research to date shows exclusion of some types of footwear. Importantly, this analysis narrows the types of footwear generally worn by missing persons for tailored research on relevant footwear information, thereby excluding extraneous or irrelevant footwear types.

. Practical applications of this research include guiding the focus of additional studies regarding missing persons' footwear. Applications include narrowing the possibilities of size, design, and other characteristics, including tread pattern of tracks made by footwear (or the lack thereof) that missing persons are wearing. Even when missing persons lose their footwear, the footwear information can also indicate probable measurements of unshod (barefoot or sock-clad) footprints (Speiden & Serrano, 2024).

Supplemental materials for this study can be found at https://tinyurl.com/MPF-materials. The authors would like to end this paper with a request for readers to submit data to the IMPFD. The questionnaire for submitting footwear data can be found through the QR code (Figure 16).

Figure 16. QR Code for the IMPFD Survey at https://tinyurl.com/mpf-survey

---

ACKNOWLEDGEMENTS

The authors would like to thank those who contributed data to this research, too numerous to list here, as well as to the time they devote to searching "…so that others may live" or know. Thanks to Melissa Weeks for editing contributions, Kimberly Williamson for excellence in footwear and other investigations, and all the SARTI Bs for their assistance with footwear investigations. Many thanks also go to the JSAR reviewers for efforts to improve the description of this research.

ABOUT THE AUTHORS

Robert Speiden has assisted with well over 500 searches as a member of several SAR groups since 1993. He responds to searches in the roles of Tracking Specialist, Search Team Leader, and Search Mission Coordinator. He has been a SAR instructor and evaluator for the Virginia Department of Emergency Management (VDEM) since 1998. Rob has published three SAR tracking textbooks: *Foundations for Awareness, Signcutting, and Tracking*; *Tracker Training*; and *Pocket Guide to Human Tracking for Search & Rescue*. Rob is currently pursuing a Master's degree in data analysis and applied statistics at Virginia Tech with the goal of advancing sciences of tracking humans.

Brian Cohan holds a Master of Science in Fire Protection Engineering from the University of Maryland - College Park. They have been involved in SAR since 2014 as an Operational Tracker, Search Team Leader, and Management Team Member. As an engineer, Cohan enjoys data visualization to help drive the questions that uncover the truth behind the data.

Joel Serrano earned his Ph.D. degree in Chemistry from Virginia Tech. He is an EMT and Search Team Leader with the Blacksburg Volunteer Rescue Squad. Joel is an Operational Tracker with the Search and Rescue Tracking Institute, and he is certified as a Level I Tracker in the Cybertracker conservation program. Through the scientific lens, Joel seeks to alleviate human suffering, if only for a moment.

REFERENCES

Abbas, A., Qamar, S., & Shahzad, M. (2020). *Factors Influencing Consumers' Preference for Purchasing Footwear Brands*. *4*, 40–52.

Albiin, N., & Eriksson, A. (1984). Fatal Accidental Hypothermia and Alcohol. *Alcohol & Alcoholism*, *19*(1), 13–22.

Andersen, J. J. (2023, September 14). *Nike Shoes Statistics*. RunRepeat - Athletic Shoe Reviews. Retrieved March 8, 2024 from https://runrepeat.com/nike-shoes-statistics

Banerjee, S., Bagchi, C., & Mehta, N. (2014). An Empirical Study on Identification of Consumer Preferences in Footwear Market Through Application of Factor, Cluster, and Conjoint Analysis. *Management Insight*, *10*(2), Article 2.

Bodziak, W. J. (2017). *Forensic Footwear Evidence: Detection, Recovery and Examination* (2nd ed.). CRC Press.

Brändström, H., Eriksson, A., Giesbrecht, G., Ängquist, K.-A., & Haney, M. (2012). Fatal hypothermia: An analysis from a sub-arctic region. *International Journal of Circumpolar Health*, *71*(1), 18502. https://doi.org/10.3402/ijch.v71i0.18502

Brown, D. J. (2009). *The Indifferent Stars Above: The Harrowing Saga of a Donner Party Bride*. HarperCollins.

Crocs.com. (2024). *Crocs Shoe Size Chart: Adult & Kids Sizing—Crocs*. Size Help. Retrieved April 22, 2024 from https://www.crocs.com/size-chart-page.html

Dave, A. A., Lehet, M., Diwadkar, V. A., & Thakkar, K. N. (2021). Ocular measures during associative learning predict recall accuracy. *International Journal of Psychophysiology*, *166*, 103–115. https://doi.org/10.1016/j.ijpsycho.2021.05.010

Diaz, D., & McCann, V. L. (2013). *Tracking Humans: A Fundamental Approach to Finding Missing Persons, Insurgents, Guerrillas, and Fugitives from the Law*. Lyons Press.

EMSA. (2010). *SearchQuestionaireICS302.pdf*. El Dorado County Colorado Emergency Medical Services. Retrieved March 8, 2024 from https://www.edcgov.us/government/ems/forms/documents/SearchQuestionaireICS302.pdf

FBI. (2016). *2015 NCIC Missing Person and Unidentified Person Statistics*. Federal Bureau of Investigation. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2015-ncic-missing-person-and-unidentified-person-statistics.pdf/view

FBI. (2017). *2016 NCIC Missing Person and Unidentified Person Statistics*. Federal Bureau of Investigation. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2016-ncic-missing-person-and-unidentified-person-statistics.pdf/view

FBI. (2018). *2017 NCIC Missing Person and Unidentified Person Statistics*. Federal Bureau of Investigation. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2017-ncic-missing-person-and-unidentified-person-statistics.pdf/view

FBI. (2020a). *2019 NCIC Missing Person and Unidentified Person Statistics*. Federal Bureau of Investigation. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2019-ncic-missing-person-and-unidentified-person-statistics.pdf/view

FBI. (2020b). *2018 NCIC Missing Person and Unidentified Person Statistics*. Federal Bureau of Investigation. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2018-ncic-missing-person-and-unidentified-person-statistics.pdf/view

FBI. (2021). *2020 NCIC Missing Person and Unidentified Person Statistics*. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2020-ncic-missing-person-and-unidentified-person-statistics.pdf/view

FBI. (2022). *2021 NCIC Missing Person and Unidentified Person Statistics*. Federal Bureau of Investigation. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2021-ncic-missing-person-and-unidentified-person-statistics.pdf/view

FBI. (2023). *2022 NCIC Missing Person and Unidentified Person Statistics*. Federal Bureau of Investigation. Retrieved September 29, 2022 from https://www.fbi.gov/file-repository/2022-ncic-missing-person-and-unidentified-person-statistics.pdf/view

Geißler, C. F., Friehs, M. A., Frings, C., & Domes, G. (2023). Time-dependent effects of acute stress on working memory performance: A systematic review and hypothesis. *Psychoneuroendocrinology*, *148*, 105998. https://doi.org/10.1016/j.psyneuen.2022.105998

GoC. (2023). *Background—2022 Fast Fact Sheet*. Retrieved April 17, 2024 from https://canadasmissing.ca/pubs/2022/index-eng.htm

Goddiess, S. (2022). The 10 largest shoe brands in the United States. Retrieved February 5, 2023, from Zippia: https://www.zippia.com/advice/largest-shoe-brands/

Gormsen, H. (1972). Why Have Some Victims of Death from Cold Undressed? *Medicine, Science and the Law*, *12*(3), 200–202. https://doi.org/10.1177/002580247201200309

Hawes, M. R., & Sovak, D. (1994). Quantitative morphology of the human foot in a North American population. *Ergonomics*, *37*(7), 1213–1226. https://doi.org/10.1080/00140139408964899

Hirvonen, J., & Huttunen, P. (1982). Increased urinary concentration of catecholamines in hypothermia deaths. *Journal of Forensic Sciences*, *27*(2), 264–271.

Hleșcu, A. A., Grigoraș, A., Covatariu, G., Moscalu, M., & Amalinei, C. (2022). The Value of Myocardium and Kidney Histopathological and Immunohistochemical Findings in Accidental Hypothermia-Related Fatalities. *Medicina*, *58*(11), 1507. https://doi.org/10.3390/medicina58111507

Hsu, J. D., Michael, J., & Fisk, J. (2008). *AAOS Atlas of Orthoses and Assistive Devices E-Book*. Elsevier Health Sciences.

Hu, R., & Jacobs, R. A. (2021). Semantic influence on visual working memory of object identity and location. *Cognition*, *217*, 104891. https://doi.org/10.1016/j.cognition.2021.104891

Hurth, J. (2012). *Combat Tracking Guide*. Stackpole Books.

James, R. R. (1965). *Gallipoli: Robert Rhodes James*. B.T. Batsford.

Kinzinger, R., Risse, M., & Puschel, K. (1991). Irrational behavior in exposure to cold. Paradoxical undressing in hypothermia. *Archiv für Kriminologie*, *187*(2), 47–56.

Koester, R. J. (2008). *Lost Person Behavior: A Search and Rescue Guide on where to Look for Land, Air, and Water*. dbS Productions.

Krispin, A., Zaitsev, K., & Hiss, J. (2011). [Death due to hypothermia and paradoxical undressing]. *Harefuah*, *150*(3), 227–229, 305.

Kuru. (2022). Most Popular Shoes by State. *KURU Footwear*. Retrieved April 16, 2024 from https://www.kurufootwear.com/a/blog/most-popular-shoe-by-state

KYEM. (2022). *Lost Person Ouestionnaire.pdf*. Kentucky emergency Management. Retrieved September 9, 2024 from https://kyem.ky.gov/Who%20We%20Are/Documents/Lost%20Person%20Ouestionnaire.pdf

Lim, C., & Duflou, J. (2008). Hypothermia fatalities in a temperate climate: Sydney, Australia. *Pathology*, *40*(1), 46–51. https://doi.org/10.1080/00313020701716466

Merriam-Webster. (2024). *Boot Definition & Meaning—Merriam-Webster*. Retrieved September 6, 2023 from https://www.merriam-webster.com/dictionary/boot

Mizukami, H., Shimizu, K., Shiono, H., Uezono, T., & Sasaki, M. (1999). Forensic diagnosis of death from cold. *Legal Medicine*, *1*(4), 204–209. https://doi.org/10.1016/S1344-6223(99)80039-X

Moreira, F. (2016). *Visual Mantracking for Law Enforcement and Search and Rescue*. CreateSpace Independent Publishing Platform.

NASAR. (2018). *Fundamentals of Search and Rescue*. Jones & Bartlett Learning.

NCA. (2014). *2012-13 Full Final Missing Persons Data Report 1.0.pdf*. National Crime Agency - United Kingdom Missing Persons Bureau. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2015). *2013-14 High Level Data Final Report 1.1 20151209 (NPM).pdf*. National Crime Agency - United Kingdom Missing Persons Bureau. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2016). *2014-15 Full Final Missing Persons Data Report 1.0 20160516 (NPM).pdf*. National Crime Agency - United Kingdom Missing Persons Bureau. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2017). *2015-16 Data Report 3.3 FINAL.pdf*. National Crime Agency - United Kingdom Missing Persons Bureau. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2019a). *2016-17 UKMPU Missing Persons Data Report 2016-2017 v 1 Final.xls*. National Crime Agency - United Kingdom Missing Persons Unit. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2019b). *2017-18 UKMPU Missing Persons Statistical Report 2017-2018 v 1.0 final 20200624.pdf*. National Crime Agency - United Kingdom Missing Persons Unit. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2020). *2018-19 Final_UKMPU Missing Persons StatsReport 201819_20201222_Revised.pdf*. National Crime Agency - United Kingdom Missing Persons Unit. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2021). *2019-20 Final Version PDF - UKMPU_Statistics_Report_2019_2020.pdf*. National Crime Agency - United Kingdom Missing Persons Unit. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2022). *2020-21 UKMPU Statistical Report 2020-2021-.pdf*. National Crime Agency - United Kingdom Missing Persons Unit. Retrieved March 6, 2024 from https://missingpersons.police.uk /en-gb/resources/downloads/missing-persons-statistical-bulletins#

NCA. (2023). *UKMPU Statistical Report 2021-2022.pdf*. National Crime Agency - United Kingdom Missing Persons Unit. Retrieved March 6, 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins

NCMEC. (2022). *Children on the Autism Spectrum: Search Protocols & Questionnaire for First Responders*. National Center for Missing & Exploited Children. Retrieved March 6, 2024 from https://www.missingkids.org/content/dam/missingkids/pdfs/children-on-the-autism-spectrum-search-protocols-questionnaire-first-responders.pdf

NEWSAR. (n.d.). *Lost/Missing Person Questionnaire*. newsar.org. Retrieved March 7, 2024, from http://www.newsar.org/Training/LOSTPersonQuestionnaireGeneric.pdf

NMPCC. (2022). *National Missing Persons Coordination Centre*. National Missing Persons Coordination Centre. https://www.missingpersons.gov.au/view-all-profiles

NPIA. (2011). *2010-11 Missing Persons Data and Analysis 2010-11 FINAL.pdf*. National Policing Improvement Agency. https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

Osuna, F. (2021). *Index Tracking: Essential Guide to Trailing Man and Beast*. Independently Published.

Ott, L., & Longnecker, M. (2016). *An Introduction to Statistical Methods and Data Analysis* (Seventh). Cengage Learning.

Robbins, R. (1977). *Mantracking: Introduction to the Step-by-step Method*. Search and Rescue Magazine.

Rockyboots.com. (2024). *Rocky Size & Conversion Chart*. Global Size Chart. https://www.rockyboots.com/global-size-chart/global-size-chart.html

Rothschild, M. A., & Schneider, V. (1995). “Terminal burrowing behaviour”—A phenomenon of lethal hypothermia. *International Journal of Legal Medicine*.

RunRepeat. (2024). *Vasque men’s and women’s size chart*. RunRepeat - Athletic Shoe Reviews. https://runrepeat.com/size-charts/vasque

Shalev, K., & Humer, C. (2022). *Podcast—Missing Persons Uncovered Series*. https://missingpersonsuncovered.com/

Shimizu, K., Shiono, H., Fukushima, T., & Sasaki, M. (1996). Paradoxical Undressing in Fatal Hypothermia. 犯罪学雑誌, *62*(5), 151–155.

Sims, C. R., Lerch, R. A., Tarduno, J. A., & Jacobs, R. A. (2022). Conceptual knowledge shapes visual working memory for complex visual information. *Scientific Reports*, *12*(1), 8088. https://doi.org/10.1038/s41598-022-12137-0

Sivaloganathan, S. (1985). Paradoxical Undressing Due to Hypothermia in a Child. *Medicine, Science and the Law*, *25*(3), 176–178. https://doi.org/10.1177/002580248502500305

Sivaloganathan, S. (1986). Paradoxical Undressing and Hypothermia. *Medicine, Science and the Law*, *26*(3), 225–229. https://doi.org/10.1177/002580248602600310

SOCA. (2013). *2011-12 Full Final Missing Persons Data Report 1.0.pdf*. Serious Organised Crime Agency. Retrieved February 28. 2024 from https://missingpersons.police.uk/en-gb/resources/downloads/missing-persons-statistical-bulletins#

Speiden, R. (2009). *Foundations for Awareness, Signcutting and Tracking*. Natural Awareness Tracking School, LLC.

Speiden, R. (2018). *Foundations for Awareness, Signcutting, and Tracking* (2nd ed.). Natural Awareness Tracking School, LLC.

Statista. (2024). *Overview of the U.S. footwear industry 2010-2022*. Statista. Retrieved March 8, 2024 from https://www.statista.com/statistics/232244/overview-of-the-us-footwear-industry/

Sterling. (n.d.). *The True Story of Shoe Sizes*. Sterling Last Corporation. Retrieved April 3, 2024, from http://www.unitedglobalsupply.com/assets/pdfs/Story%20of%20Shoe%20Sizes%20-%20Sterling%20-%20UGS.pdf

Stoffel, B. C., & Stoffel, R. C. (2017). *Managing the Inland Search Function*. Emergency Response International.

Taylor, A., & Cooper, D. C. (1990). *Fundamentals of Mantracking: The Step-by-Step Method* (Second). Emergency Response Institute, Inc. and National Rescue Consultants, Inc.

Taylor, A., & Cooper, D. C. (2014). *Fundamentals of Mantracking: The Step-by-Step Method: An Essential Primer for Search and Rescue Trackers* (3rd ed.). Skyhorse Publishing.

UCSO. (2014). *Lost Person Questionnaire 2014*. Utah County Sheriff's Office. https://sheriff.utahcounty.gov/forms/LostPersonQuestionnaire2014_1.pdf

USCB. (2024). *United States Census Bureau QuickFacts*. Retrieved March 7, 2024 from https://www.census.gov/quickfacts/fact/table/US/PST045222

Vejlens, G. (1952). Kanslan av betta vid forfrysning [The Feeling of Heat in Congelation]. *Nordisk Kriminalteknisk Tidsskrift*, *22*(12), 141–143.

VSP. (2006). *Virginia Missing Person Information Clearinghouse Report*. Virginia State Police. https://vsp.virginia.gov/wp-content/uploads/2021/07/SP-067_Va_Missing_Person_Info_Clearinghouse_Report.pdf

Wedin, B., Vanggaard, L., & Hirvonen, J. (1979). "Paradoxical undressing" in fatal hypothermia. *Journal of Forensic Sciences*, *24*(3), 543–553.

Young, C. (2021). *Intelligent Search: Managing the Intelligence Process in the Search for Missing Persons*. dbS Productions.

Zupko, R. E. (1977). *British Weights & Measures: A History from Antiquity to the Seventeenth Century*. University of Wisconsin Press.

TECHNICAL REPORT

Bolts Are Not Nails: Overcoming Misconceptions about Wedge Bolt Use in Permanent Rigging

William K Storage
Amy F Skowronski

Email storax101@gmail.com

http://dx.doi.org/10.61618/CFRA9389

Abstract

Considerable misinformation circulates in mountaineering and cave exploration circles concerning the torque needed to correctly install the wedge anchors used in technical rigging. Misunderstanding the proper operation of wedge bolts has caused serious accidents. This explanation of bolt physics defends the installation of bolts using the torque specifications given by manufacturers and engineering guidelines against the common beliefs of many who install them for climber protection and permanent rigging.

KEY WORDS: *bolted joint, wedge bolt, permanent rigging, physics, engineering mechanics, shear force*

Introduction

Understanding how wedge bolts work can save your life. This article is an explanatory analysis, not instruction or original research. It describes how wedge bolts are designed to work and how they are often misunderstood and misused. Serious accidents have resulted from unwanted bolt pullout (Orndorff, 2022, Williamson, 2012).

A great deal of misinformation, inconsistent with mechanical principles, the laws of physics, and abundant industrial evidence is on the web and in the communities of climbers, cavers, and rescuers that use bolts. Accomplished climbers, for example, have emphatically stated that over-tightening the nut on a 3/8-inch wedge bolt is a significant risk. It is not. Engineers' perspectives are in fact the opposite, as observed by John Bickford (1995) in the classic text, *Introduction to the Design and Behavior of Bolted Joints*: "How much preload? We always want the maximum possible." Climbers often see it differently.

> *"The only reason for tightening anchors at all is to ensure the grabbing mechanism is engaged. This is easily achieved with very little torque. If you want additional insurance the mechanism will remain engaged over time I recommend using a locknut and/or lockwasher."*
>
> *"The pre-load of the bolt is only used to keep the bolt from coming loose during cyclic loading. In my opinion, the lowest possible torque that will prevent the bolt from loosening is the ideal."*
>
> *"When placing bolts I've come to use the rule of finger: I tighten to snugness and then some with a couple fingers."*
>
> *"I have no doubt I could twist the head off a bolt with a 6" wrench and have had friends actually do it several times."*

Discussion

The following analysis applies to wedge bolts and sleeve bolts only (fig. 1, below). Sleeve bolts were invented for use in weak materials like cinderblock, and extensive testing by Caltrans (Dusel, 1981) showed them to have poor pullout performance. A ⅜-inch wedge bolt has 50% more cross-sectional area because ⅜-inch is the hole diameter, not the sleeve bolt shank diameter. For those reasons we'll use wedge bolts as the subject of this piece, and ⅜-inch diameter because they're popular in the US.

Wedge bolts have a solid shaft threaded on one end and an integral expander cone on the other end. A collar around the base of the bolt gets forced up the expander cone and into the rock as one tightens the nut. The physics of self-drives, concrete screws, and glue-in anchors is completely different and will not be covered here. This article assumes good, solid rock, though it need not be homogeneous or isotropic.

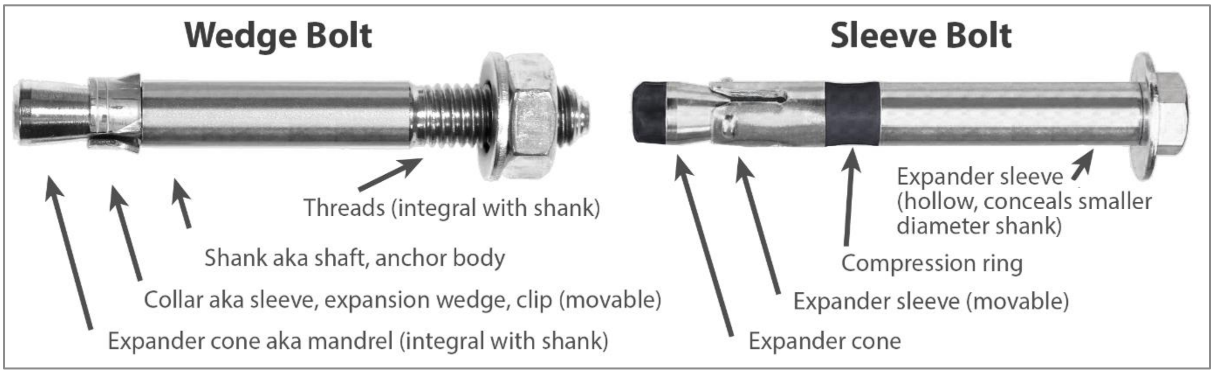

Fig. 1 Nomenclature for wedge and sleeve bolts.

This article uses only two physical principles, also called laws of nature, and prior knowledge of them isn't required. First is Newton's 3rd Law: for every action there is an equal and opposite reaction. If A pushes on B, B pushes back with an equal force. Second is the Law of Friction: friction force is proportional to the perpendicular force (“normal” force, in physicist parlance) exerted between surfaces. Proportionality in this context means that if the squeeze force doubles, the friction force also doubles.

Wedge bolts, like nails, rely on friction to do their job. But the underlying mechanisms of bolts and nails are very different. The first climber quote listed above, for example, reveals that he understands wedge bolts to function as nails, with the barbs on the collar providing the needed friction. If you use a wedge bolt in rock as you would use a nail in wood, it will not work as its designers intended. If you use a wedge bolt in an overhang or the ceiling of a cave as if it were a nail, tragedy is likely.

For each combination of materials involved in friction, there is a constant ratio, called *coefficient of friction*, between the squeeze force and the friction force. The coefficient is 0 for two perfectly slippery surfaces, and 1 for infinitely sticky surfaces. Real-world values fall somewhere in between. Though ice skaters are heavy, the coefficient of friction between skates and wet ice is close to 0, so the frictional force opposing the skater’s motion is tiny. In equation form, friction F equals coefficient μ times perpendicular force N. $F=\mu N$. This is the Law of Friction in equation form.

When you hit a nail with a hammer, the nail pushes the wood fibers apart, and the wood fibers push back on the nail. The force needed to drive a nail (F in the Law of Friction) equals the force with which the wood squeezes down (N, above) on the nail, times the coefficient of friction (μ) between nail and wood. The force required to pound a nail in is the same force required to pull it back out.

Bolts rely on friction, but in a more complex way. When you pound a wedge bolt into a good hole, you need to hit it hard, as when you pound a nail. Unlike the case with nails, this hammering force, caused by the barbs on the collar, has nothing to do with the force required to pull a *properly placed* wedge bolt out of its hole. Nothing.

Fig. 2. Resistance to pounding a wedge bolt into its hole comes from the barbs on its collar and is unrelated to the force needed to pull a properly placed wedge bolt out of its hole. In ceiling placement, friction caused by the barbs may even sustain someone's weight if the barbs. But, unlike the case with a preloaded bolt, every increment of applied load adds to the load felt by the bolt and its barbs, resulting in an unsafe joint.

As you apply torque, the collar contacts the sides of the back end of the hole. For you to feel resistance as you tighten the nut, the rock has to apply the same torque (Newton's 3rd law, in this case called Conservation of Angular Momentum) in the opposite direction. As long as the bolt hole is round (e.g., as opposed to a keyed hole), the only possible source of this opposing torque is friction between the hole and the collar. Thus, there is no mechanism by which you can tighten the nut and not have the collar seated in the hole.

When we join two parts together, like two girders, with a bolt, we call the assembly a bolted joint. Similarly, a wedge bolt connecting a hanger to a rock wall is a bolted joint. As the nut is tightened (or *torqued*, the term used below for emphasis), an immense friction force builds up at the expander cone and collar. This frictional force creates an axial stretching (tension) force in the bolt, which is exactly equal to the squeezing force the bolt applies to the rock, parallel to the bolt.

When you then use a horizontally-placed bolt by applying working loads underground, in most use cases there is not much pullout force on the bolt. The applied load is downward, perpendicular to the axis of the bolt. In construction and engineering, this situation is typically called a *shear joint*. Climbers, trainers, and web videos often say that, in this most common vertical-load case, the bolt is "loaded in shear." This is incorrect, however. Loading a properly assembled shear joint does not induce a shear force in the bolt used to make that joint.

A bolted joint where the load is in line with (in the direction of) the boot is commonly called a *tension joint*. A bolt placed in a ceiling where the load pulls downward is an example of a tension joint. Loading a properly assembled tension joint does not load its bolt in either shear or tension.

The absence of shear or tensile force in the bolt within shear and tension joints is counterintuitive for many people. This aspect of bolted joints is the magic of bolts (*bolts* in the engineering sense, which excludes screws having no nut, glue-ins, and anything that works like a nail). Loads applied to the joint, typically through a bolt hanger in mountaineering usage, are not transmitted to the joint's bolt. The work to install the bolt equals the work put into torquing the nut. It is the energy bound up in the bolt, which is being stretched, and in the rock, which is being squeezed. The amount of stretching force in the bolt is always exactly equal to the squeezing force applied to the rock. That force is called the *preload force*.

If a hole is too wide for the bolt because the drill was wobbly or the rock is crumby, the collar around the expander cone may never engage. In that case tightening the nut may just back the bolt out of the hole with little resistance - that is, without much torque. Or the collar might have enough friction with the hole interior to keep the bolt from backing out, but not enough friction to keep the shank from spinning, again resulting in not building up torque and preload.

If the amount of torque required by the design of the bolt isn't applied, the bolt does not get preloaded, and the joint cannot prevent applied loads from loading the bolt. This is the important part. Preload - and a lot of it - is essential to a properly placed bolt. Preload prevents the stress states in the bolt and in the rock from changing when a load is applied.

Preload - and a lot of it - is absolutely essential to a properly placed bolt.

The desired preload is always a large fraction of the amount of force that would permanently deform the bolt. This is desirable, done on purpose, and integral to the way threaded fasteners were designed to work. In critical applications such as aircraft, bolted joints are often specified to use a preload force *greater than* the point of permanent ("*plastic"*) deformation.

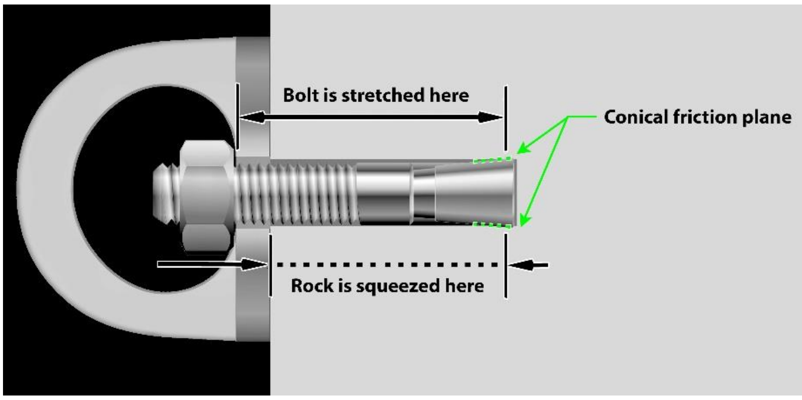

Fig. 3. Idealized hanger with a torqued nut showing equal and opposite stretching and squeezing forces and the regions where stretching and squeezing occurs.

For a ⅜ inch bolt with no grease applied to the threads, the torque needed for proper preload, according to both manufacturers' guidelines and engineering calculations, is about 28 foot-pounds [38 Nm] (Powers gives 28, Confast, 30). That's an extended 28-pound [125 N] tug on a one-foot wrench or a 56-pound [250 N] yank on a six-inch wrench (more like 80 pounds [350 N] because of where your hand ends up on a wrench). Putting that much force on a wrench handle is difficult and painful when you are pushing downward. Pushing sideways, as when a bolt is in the ceiling, with that much force while you are hanging in a harness is harder still.

Yield strength is the load that causes the onset of permanent deformation. *Ultimate strength* is the load to break the bolt. The ultimate strength of a 304 bolt is at least twice its yield strength (NASA, 1979). Specified torque values for 304 bolts are typically 65-75% of that which would yield the bolt (NASA, 2017). Thus the torque needed to break a 3/8 304 bolt is at least 60 foot-pounds [80 Nm], provided it didn't pull out. Therefore, despite anecdotes, the likelihood of breaking ⅜ bolts with hand wrenches is quite remote.

For the remainder of this article, we'll use as an example, ⅜ bolts torqued to 28 foot-pounds, causing a preload of 3000 pounds [13.3 kN]. Because of variability of friction coefficients in the bolt/nut/hanger interfaces due to environmental factors, the preload could range between 2500 to 5200 pounds [11,000 – 23,000 N]. We'll use 3000 pounds henceforth, a bit less than half the strength of the bolt, for our examples here.

Assuming 3000 pounds of preload, and therefore 3000 pounds of rock-squeeze, let's hang a 200-pound person from a bolt placed vertically in the ceiling. What is the resulting tension in the bolt? One might think it is 3200 pounds - the sum of the preload force and the person's weight. But that is not what happens, and the preload is why.

The mechanical properties of the relatively small bolt differ greatly from those of the big slab of rock. The steel is ductile and elastic, and the rock is stiff by comparison. The preload in the bolt, combined with the mechanical properties of the bolt and the rock, set up a situation where the load applied to the hanger does not increase the load in the bolt at all - not until the applied load gets close to the 3000-pound preload. Here it helps to remember that we hang on the hanger, not the bolt. The hanger does *not* transmit the 200-pound load to the bolt. Instead the weight of a 200-pound [900N] person merely decreases the squeeze force between the rock face and the hanger - from 3000 pounds down to 2800 pounds. This is why aircraft bolts are often torqued beyond their yield strength, by specification, to prevent the bolt from "feeling" any applied load. It cyclical-loading scenarios, the preload also prevents the bolt from feeling load oscillations that cause fatigue failures.

From here on, in our examples we'll increase the applied load from 200 to 1000 pounds to better make the case.

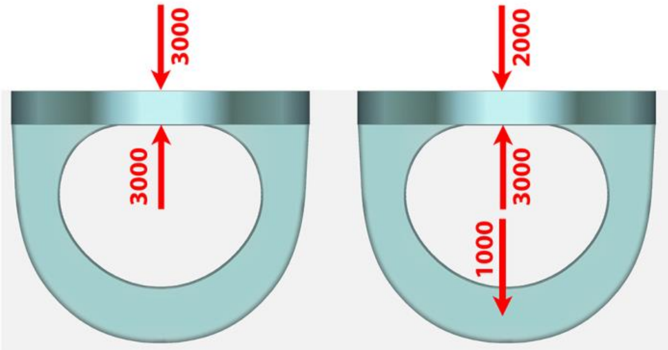

Fig. 4. Idealized hangers showing forces transmitted by bolt, rock, and 1000-pound applied load. Length of arrows does not indicate magnitude of force.

Consider only the external forces acting on an idealized hanger (not bolt) attached to a preloaded bolt. Compare the cases with no applied load (fig. 4, left) and with an applied load of 1000 pounds [4450 N] (right). In both cases the nut pushes *up* on the hanger with a force of 3000 pounds. With no applied load, the wall pushes *down* with an equal but opposite 3000 pounds. Net external forces on the hanger will always sum to zero (Newton's 3rd Law). With a 1000-pound applied load, the wall pushes *down* with 2000 pounds and the nut continues to push *up* with 3000 pounds. Net external forces on the hanger still sum to zero.

To further clarify, consider, as an analogy, a loaded spring scale where we intentionally block the spring from retracting (fig. 5).

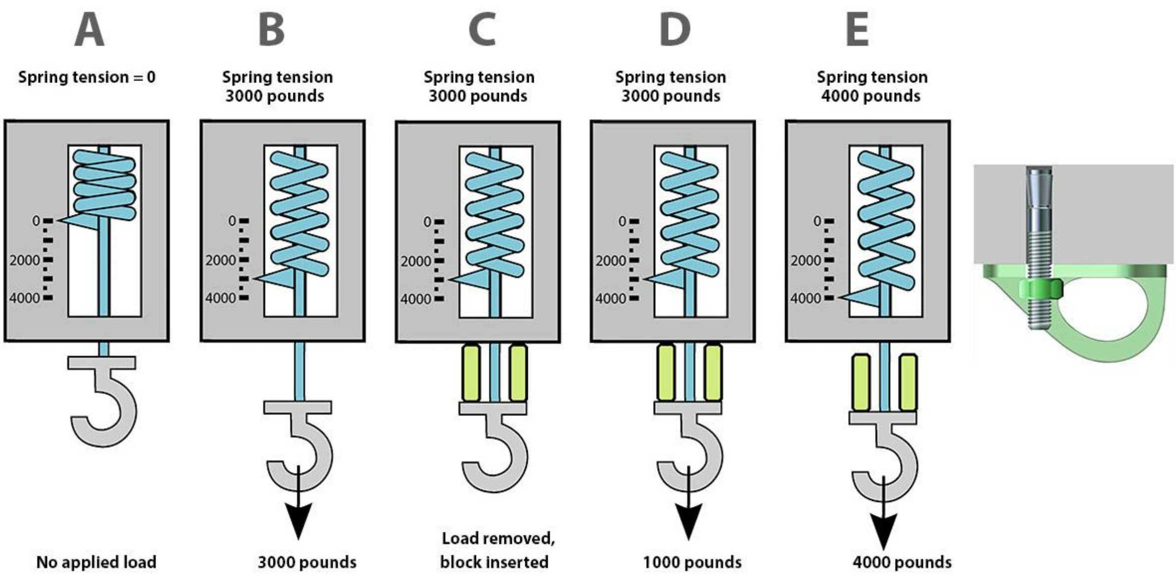

Fig. 5. A spring scale is a good analogy for wedge bolt placed in the ceiling. In state A, the spring is not loaded and therefore is not in a state of stress. In B we hang a 3000-pound load and the spring stretches so that the indicator reports the load. The spring is in a state of tensile stress. In C, we slip blocks between the flat top of the hook and the housing of the scale, thereby preventing the spring from retracting. There is no weight of the scale, but the block causes the spring to remain stretched and in tension. It is now preloaded with 3000 pounds of force. In D, we hang a 1000-pound weight from the scale's hook, noting that the blocks are still in place. The stress state of the spring, and the preload force within it, do not change at all. In E we hang a 4000-pound load, which exceeds the existing preload. The blocks separate from the bottom of the scale's housing and the tension force in the spring is now 4000 pounds.

Labeling the forces both on the hanger (hanger forces shown in red) and on the bolt (in blue, fig. 6, below) for the same two cases shown in figure 4 demonstrates how the bolt and hanger forces relate to each other. In this example we neglect the small effect of the offset between the carabiner hole and the bolt. That offset does not "lever the bolt" as reported by several instructional sources – again, because of the preload.

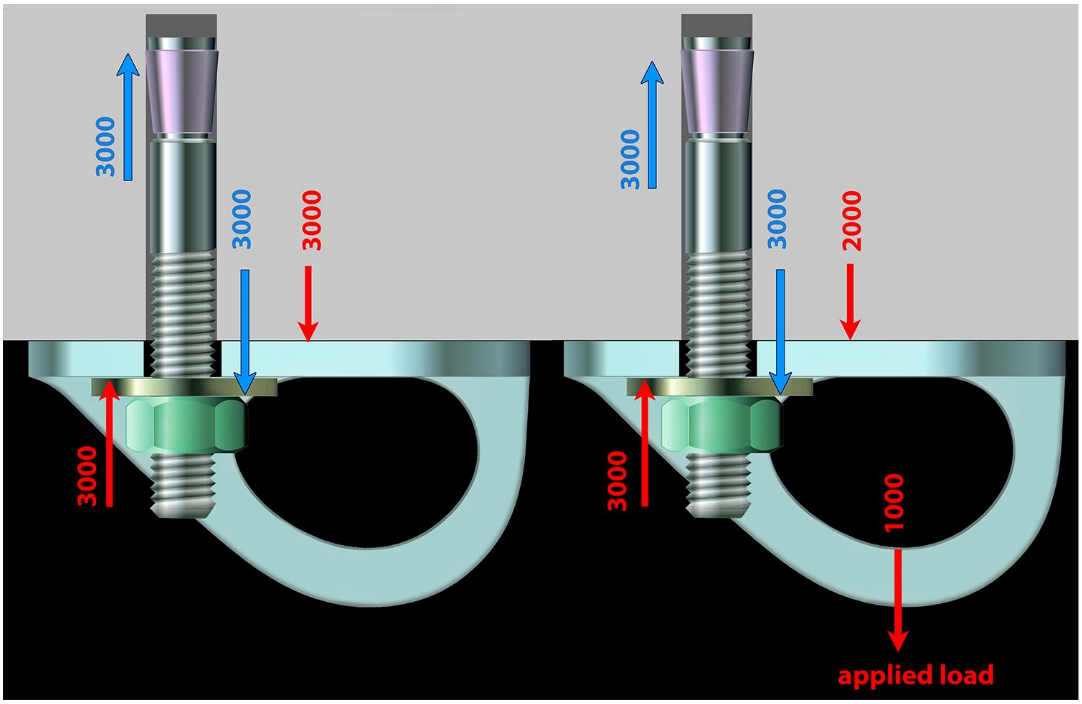

Fig. 6. At left the nut is torqued to 28 foot-pounds. The torque causes the nut to pull downward with a 3000-pound tension force on the bolt. The rock at the back of the hole pulls upward with 3000-pound tension force on bolt through its collar. The bolt is preloaded to 3000 pounds. The nut pushes upward on the washer, which pushes upward on the hanger with a 3000-pound force due to the nut being torqued. The rock wall (ceiling) pressed downward on the hanger with a 3000-pound force. The hanger is being squeezed with 3000 pounds. The forces on the hanger balance out and sum to zero. The forces on the bolt also add up to zero.

At right the nut is torqued and 1000-pound load is hung from the hanger. The torque causes the nut to pull downward with a 3000-pound tension force on the bolt. The rock at the back of the hole pulls upward with 3000-pound tension force on bolt through its collar. The applied load of 1000 pounds pushes down (or pulls down, depending on how you look at it) on the hanger. This reduces the force with which the rock pushes down on the hanger to 2000 pounds. The nut pushes upward on the washer, thereby pushing upward on the hanger with a 3000-pound force. The rock ceiling pressed downward on the hanger with a 2000-pound force. The forces on the hanger balance out and sum to zero. The forces on the bolt also add up to zero. The bolt is still preloaded to 3000 pounds.

Another counterintuitive consequence of preload is that a preloaded horizontal bolt is never loaded in shear. It is always loaded in pure tension, before and after any reasonable vertical load is applied. Any applied vertical load is transmitted by the hanger to the rock face by friction. So, until the applied load is equal to the coefficient of friction times the preload force, the hanger never pulls down on the bolt itself. The bolt feels no shear force.

The below diagram shows the forces in the hardware, with a load pulling down on a bolt with a loose nut, with a hand-tightened nut, and with a properly torqued nut. In all cases, both the horizontal and vertical forces sum to zero. Here we neglect the small effect of the offset between the carabiner hole and the wall.

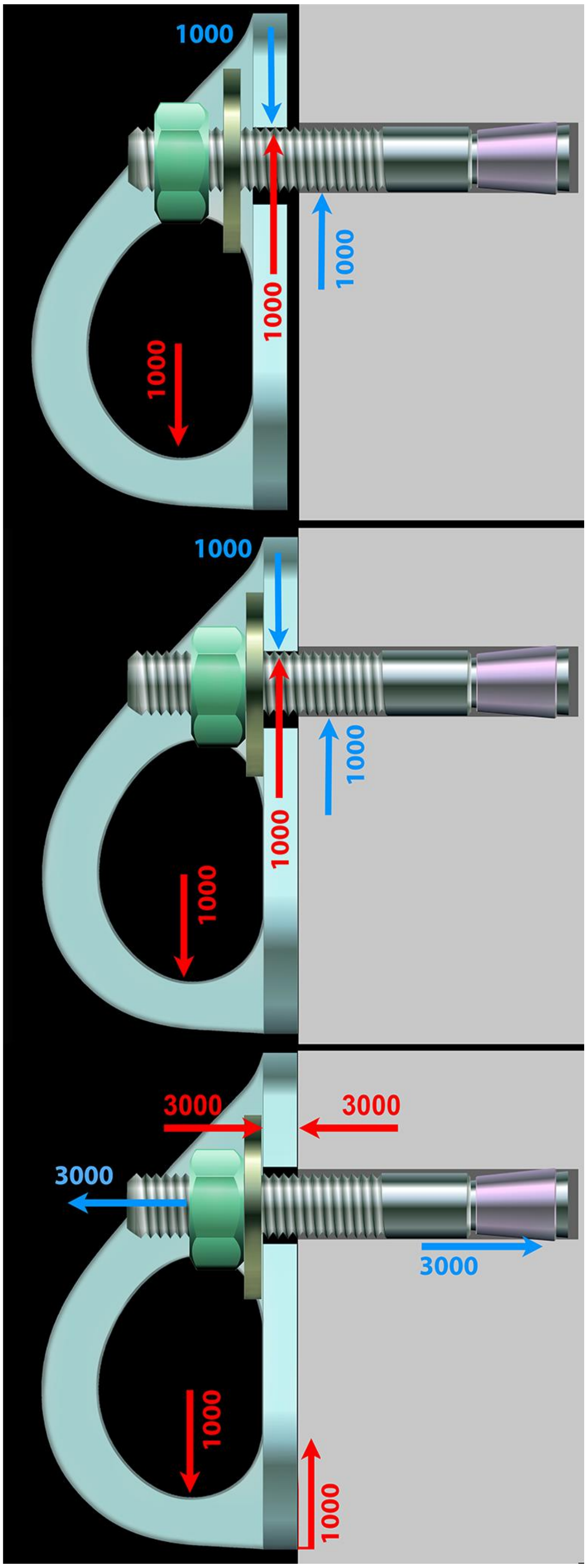

Fig. 7. The nut, washer, and hanger are loose on the bolt (nut is not torqued). The bolt is not preloaded. No tension force is in the bolt.

An applied 1000-pound load pushes down on the hanger. The bolt pushes upward on hanger with a 1000-pound force in the opposite direction. The hanger pushes downward on the bolt with 1000 pounds. The rock pushes up on the bolt with 1000 pounds. The bolt is loaded in shear.

"Push" and "pull" help us talk about the situation using natural wording but are not important to what is going on. Only the direction and size of the forces matter.

The nut is hand-tight against the washer hanger, and rock face. The bolt is not preloaded. No tension force is in it.

An applied 1000-pound load pushes down on the hanger. The bolt pushes up on hanger with a 1000-pound force in the opposite direction.

The hanger pushes downward on the bolt with 1000 pounds. The rock pushes upward on the bolt with 1000 pounds. The bolt is loaded in shear. Its threads are loaded in a way not intended by the manufacturer.

The nut is torqued to 28 foot-pounds. The nut applies a 3000-pound tension force (to left) on the bolt. The rock pulls to the right with a 3000-pound tension force on the collar of the bolt, which pulls to the right with the same force on the bolt shank. The bolt is preloaded with 3000 pounds of tension force. The hanger is being squeezed with 3000 pounds. The bolt is not loaded in shear. No vertical forces act on it.

A 1000-pound applied load pulls downward on the hanger. The rock wall pushes upward on the hanger with a 1000-pound frictional force.

Like the climbers' quotes above, sources of instruction on bolting often teach that very low torque values can or should be used in the standard horizontal-bolt situation shown above. They are thus calling for no bolt preload and using bolts as if they were nails. The load required to pull the bolt out will be the amount of force it took to hammer it in – not very much.

For a horizontal bolt with no preload, the bolt *is* in fact loaded in shear (the first two scenarios in fig. 7). The hanger bears down on the bolt and transfers the entire vertical load to it. ⅜ inch bolts can handle this except for ruining the threads. The absence of preload can go unnoticed for years - until the dynamics of a fall happen to place a horizontal (pullout) load on the bolt. This can happen during a fall, for example, if the belayer is at some horizontal distance from the first bolt or in rescue scenarios with hauling systems.

Bolts in a ceiling with inadequate preload are deadly. The nail analogy applies; the force to pull it out equals the force it took to push it in. An improperly torqued ceiling bolt may even sustain someone's weight if the barbs on the collar can provide friction equal to the applied load, which is now along the axis of the bolt. But, unlike the case with a preloaded bolt, every increment of applied load now *does add* to the load felt by the bolt, thereby calling on the bolt-rock interface to oppose that load with an equal frictional force. But friction can only do so much, because friction is relying solely on collar barbs inside of the hole. Some wedge bolt designs, particularly the geometry of the barbs on the collar, (e.g. Raumer) (Orndorff 2022), result in comparatively high pounding force to push the bolt into its hole. This exacerbates the problem of equating pounding force with preload.

Industrial experience and a mechanical analysis of this application of bolts allows us to make some very strong claims about wedge bolts. Most importantly, a bolt's nut must be properly torqued to achieve the preload that prevents the bolt from feeling any later-applied load. Correspondingly, it is virtually impossible for a bolt having preload to pop out of the hole. There is no mechanism by which nut torque can exist in a good bolted joint without the bolt having preload.

Preload is, within reason, the only thing that matters for a properly installed bolt. Preload can't exist if the hole diameter is too large or if the rock is horribly weak. It's also useful to consider the things that don't really matter in judging whether a bolt placement is good. The number of threads protruding through the nut is no indication that the nut was tightened. A hole that wasn't blown clean and contains rock dust might stop a bolt from being torqued and preloaded, but if you were able to apply 28 foot-pounds of torque, the bolt is preloaded and it will hold, dust or not. The brand of drill affects how tired your arm gets and your ability to make a good hole but has no bearing once the nut is torqued. We all have our favorite brands of bolts, but all ⅜ stainless bolts with 16 threads per inch create the same preload for a given amount of torque. The preload is a function of thread pitch, the steel-on-steel coefficient of friction, and the elastic modulus of the steel, which does not vary by brand. Bolt preload, regardless of bolt orientation, ensures that when you apply a load to it there will be no change in the stress state of either the bolt or the rock it is in.

Bolt preload, regardless of bolt orientation, ensures that when you apply a load to it there will be no change in the stress state of either the bolt or the rock it is in.

Measurements of metal creep, the relaxing of the preload stress in a bolt, vary widely depending on conditions. Where vibration is not a factor, a 10% loss of preload is commonly reported within a few days (e.g. MIL-HDBK-60, 1990; Chesson, 1964). Caltrans data showed some instances of loss of over 25% (attributed to steel creep, not concrete weathering – Honarvar, 2017) in 30 years.

Fig. 8. Training with a torque wrench or similar setup helps learn what 28 foot-pounds feels like when applied with a hand wrench.

Given the importance of preload, it makes sense to learn what 28 foot-pounds feels like on the wrench you use to place bolts. A torque wrench fixed to a bench, against which a trainee uses a hand wrench as would be the case in the field, might be a good addition to rigging training. Given the extensive misunderstandings regarding bolt installation, it is likely that a large fraction of existing bolt placements have no preload. Periodically retorquing the nuts on existing permanent rigging seems prudent and is absolutely essential when rescue work makes use of existing rigging.

Disclaimer: This document was written for the consideration of experienced and properly trained rescuers, cavers, and climbers only, and is not intended as instruction. The authors do not make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information presented herein.

About the authors

William Storage is an engineer with extensive experience in design and failure analysis of bolted joints and has served as expert witness in many aircraft crash accident analyses and court cases involving threaded fasteners and bolted joints. He has installed hundreds of wedge anchors for mountaineering and caving in the US, Canada, and Mexico.

Amy Skowronski is a construction project engineer with extensive experience in aluminum and austenitic stainless metal fabrication and welding. She has a passionate commitment to both the technical aspects of equipment design and its human aspects including ergonomics, error prevention, and usability.

References

Bickford, J. *An Introduction to the Design and Behavior of Bolted Joints (Mechanical Engineering, Volume 97)* 3rd Edition, Marcel Dekker, 1995.

Dewalt (Black and Decker Corporation). *Dewalt (formerly Powers) Technical Guide – Mechanical Anchors, Revision B*, 2022.

Department of Defense. *MIL-HDK-60: Threaded Fasteners - Tightening to Proper Tension,* Mar. 1990.

Dusel, John P. "Evaluation of Mechanical Expansion Anchors" in *Transportation Research Record, Issue No.1223, Bridge Design and Performance and Composite Materials,* Transportation Research Board of the National Academy of Sciences, 1981.

Chesson, E., Jr. and W.H. Munse. "Studies of the Behavior of High Strength Bolts and Bolted Joints" in *University of Illinois College of Engineering, Engineering Experiment Station Bulletin 469,* 1964.

Honarvar E., S. Sritharan, M. Rouse, California Department of Transportation. *Effects of Superstructure Creep and Shrinkage on Column Design in Posttensioned Concrete Box-Girder Bridges,* p.119, Feb 2017.

NASA. *Mechanical Properties and Oxidation and Corrosion Resistance of Reduced Chromium 304 Stainless Steel Alloys,* NASA Technical Paper 1557, 1979.

NASA, *Installation Torque Tables for Noncritical Applications*, NASA/TM—2017-219475, 2017.

Orndorff W., T. Malabad, T. Polson, J. Delafield. *Recent Failed Bolt Placements in Virginia*, VPI Cave Club forum, cave-club-g@vt.edu, Jul 28, 2022.

Williamson, J., Ed. "Protection Bolt Pulled Out, West Virginia, Meadow River," in *Accidents in North American Mountaineering*, p. 97, American Alpine Club, 2012.

LETTER TO THE EDITOR

Evaluating Techniques and Equipment in Water Rescue: Are We Doing Enough?

Lawrence Harris
Technical Director
WRS International BV
Menen
BELGIUM

Email: lawrence@wrsinternational.com

http://dx.doi.org/10.61618/XSAX1578

Dear Editor,

Water rescue is a critical area of safety that warrants careful examination, particularly in the context of how we approach training, equipment provision, and rescue techniques. During my experiences with various organizations—ranging from rescue professionals to industries seeking solutions to their challenges—I have observed a significant disparity in the strategies employed for water rescue compared to those utilized in Working at Height scenarios.

The Importance of Equipment and Training

In my role as a Work at Height consultant, I was often called upon to devise solutions for safe working environments and to formulate comprehensive rescue plans. This process typically included a thorough evaluation of the equipment needed based on these plans. Companies were generally receptive to technical advice, driven by concerns about safety, potential legal repercussions, and the stark reality of what falling from height can entail.

In contrast, the water rescue sector appears to lag behind in similar vigilance. While there is certainly a focus on training and the acquisition of equipment—often limited to basic awareness courses—many organizations seem to underestimate the complexities and risks associated with water environments. Water is frequently perceived as a lesser threat, with the belief that basic swimming skills are sufficient for survival. However, this mindset is fundamentally flawed, and drowning remains a significant risk even for those who are proficient swimmers.

The Role of Experienced Professionals

An experienced rescue professional can play a pivotal role in helping teams and companies prepare for water-related incidents. Their insights can be invaluable in identifying potential weaknesses in current systems and equipment provisions. By understanding the unique dynamics of a water environment, a professional advisor can provide fresh perspectives that may highlight pitfalls overlooked by those immersed in day-to-day operations.

For example, many organizations may invest in Personal Protective Equipment (PPE) but fail to incorporate it into a comprehensive water rescue strategy. This approach can lead to gaps in preparedness that could jeopardize both rescuers and victims during actual emergencies. A thorough risk assessment, coupled with practical training tailored to specific environments, can greatly enhance safety outcomes.

The Importance of Expertise in Water Rescue

In the realm of water rescue, having a well-rounded rescue professional on hand is crucial. While teams may enhance their skills through rigorous training courses, such as the UK Defra Module courses provided by reputable organizations, the depth of knowledge on river hydrology often remains limited. This is where the insight of experienced water users becomes invaluable.

Understanding River Dynamics

Experienced water users possess a nuanced understanding of river dynamics that goes beyond basic rescue techniques. They can evaluate the potential effects of water currents, eddies, and obstacles on a person's ability to recover from a fall or other incident. Their familiarity with local water conditions allows them to anticipate the challenges that may arise during a rescue, enabling more effective and timely responses.

River reading skills—understanding how water behaves and the dangers it can pose—are not easily acquired. They require years of experience, observation, and practice to perfect. These skills include recognizing varying water levels, identifying hazardous features such as submerged rocks or strong currents, and predicting how these elements interact with one another. Such knowledge can be the difference between a successful rescue and a tragic outcome.

Learning from Experience

The reality is that learned mistakes in water rescue can have profound consequences. The risks associated with water incidents are multifaceted and can escalate quickly. An organization that underestimates the complexity of the water environment may find itself ill-prepared during a crisis. Engaging with skilled professionals who have honed their river reading abilities can help avoid these pitfalls.

These experts can provide valuable insights into best practices, equipment choices, and rescue strategies tailored to specific locations and scenarios. By leveraging their experience, organizations can develop robust rescue plans that account for the unique characteristics of the water bodies in which they operate.

Building a Culture of Safety

Both rescue and industrial organizations should prioritize consultation with seasoned water professionals as part of their safety protocols. This not only enhances operational readiness but also fosters a culture of continuous improvement. The insights gained from experienced individuals can be incorporated into training programs, ensuring that all team members are equipped with a comprehensive understanding of the risks and techniques associated with water rescue.

In summary, while formal training courses provide essential skills, they cannot replace the experiential knowledge gained from years of navigating and understanding water environments. Seeking the opinion of skilled individuals in the field is not just beneficial—it is imperative for the safety and effectiveness of water rescue operations. By doing so, organizations can mitigate risks and enhance their readiness for potential emergencies, ultimately saving lives and avoiding tragic outcomes.