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DCIEM 98-P-74

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Applied Ergonomics 31 (2000) 361-369

APPLIED ERGONOMICS

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Helmet accommodation analysis using 3D laser scanning

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Received 6 December 1998; accepted 5 January 2000

Abstract

A method used to determine the probable population accommodation of a helmet sizing system is described. The method involves the use of 3D laser scanning, as a means of measuring helmet standoff distance (distance between the inside of the helmet and the skull), and the selection of a representative sample of test subjects. The laser scanner and the software developed to calculate standoff distance proved to be an excellent tool for the assessment of helmet fit. The main advantages include ease of use and visualization of problem areas. This 3D-analysis method gives designers objective evidence of the need for design changes as well as an idea of what these changes should be. A comparison was made between standoff distance results obtained from the scanner and those obtained using a physical measurement method (a probe). Although discrepancies were found between the two, sources of errors intrinsic to both methods make it difficult to determine which of the two methods yielded the truest standoff distance. Analysis of the comparison data shows laser scanning to be slightly more conservative than the probe method for standoff distance purposes, i.e. erring on the side of safety. © 2000 Published by Elsevier Science Ltd. All rights reserved.

Keywords: 3D anthropometry; Laser scanning; Helmet accommodation

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1. Introduction

Today's ballistic helmets are designed and manufactured to exacting requirements using state-of-the-art materials. However, the latest manufacturing technology and materials alone are not sufficient to guarantee satisfactory protection of the wearer's head. In order to be efficient and safe, the shape and size of the helmet shell must conform as closely as possible to the heads they are intended to protect. This goal is made more difficult to accomplish by the fact that the anthropometric information available to most designers (i.e. traditional anthropometric measures that require Frankfort plane orientation) is misleading and can lead to poor helmet sizing (Robinette and Whitestone, 1994). Many examples exist of helmets that were too bulky and uncomfortable or that did not accommodate the range of users they were designed for (Hickey, 1992; Bruckart et al., 1993; Robinette and Whitestone, 1994). Part of the problem came from the lack of appropriate tools (prior to the advent of 3D laser scanning) to measure the spatial relationship between the head and the helmet (Robinette et al., 1997).

Three-dimensional head scanning has opened a new realm to helmet design and evaluation. New techniques have been developed to provide helmet-based reference systems and techniques to acquire and analyse helmet fit data (Robinette and Whitestone, 1992; Robinette, 1993; Whitestone, 1993). With the insight provided by graphical representation and analysis of the relationship between the head and the helmet, helmet fit can be assessed with a greater degree of accuracy. Designers and users are now able to assess population accommodation in a systematic way and determine the optimum sizing system. This paper describes an approach that makes use of 3D laser head scanning to evaluate a helmet sizing system's accommodation of the user population.

2. Method

The term "fit" can have an objective as well as subjective connotation. In this study, the definition of fit was purely objective. A helmet was deemed to fit if the

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PII: S0003-6870(00)00006-5

"standoff distance", i.e. the distance between the inside of the helmet and the skull of the wearer, was greater than 12.5 mm as measured to the nearest 0.5 mm. Standoff distance is required for two principal reasons: to provide a buffer zone against the after-effects of projectile impact (back-face deformation), and to provide a path for effective air circulation for convective head cooling. Standoff distance is usually measured using depth probes through holes drilled in the helmet. This approach is laborious and only provides spot checks over the surface of the head. An alternative approach is to use three-dimensional laser scanning to capture surface data on the head and helmet and calculate the distance between the two.

2.1 Equipment

A Cyberware 3030 RGB scanner with a PS platform was used to scan the subjects (Fig. 1, r.h.s.). The scanner was operated through a Silicon Graphics Indigo2 workstation with an Extreme Graphics card. Shapeanalysis (software from Beecher Research Company) was used to merge and combine the files, as required. A helmet accommodation module was developed under contract for this application (Beecher, 1993). The spatial resolution quoted by the manufacturer for this scanner is between 0.5 and 2 mm in the x-axis (depending on the motion platform speed), 0.628 mm in the y-axis, and between 0.100 and 0.400 mm in z-axis. Calibration of the instrument using a cylinder of known diameter (measured to ±0.001 mm using a micrometer) showed a slight bias of −0.11 mm. Repeated scans of the cylinder showed that the measurements were within 0.08 mm of the mean cylinder diameter, 95% of the time. Probe measurements were taken using a Mitutoyo Digimatic caliper model CD-6″C (Fig. 1, l.h.s.). A resolution and repeatability of 0.01 mm are quoted by the manufacturer, and the instrumental error is quoted as ±0.02 mm.

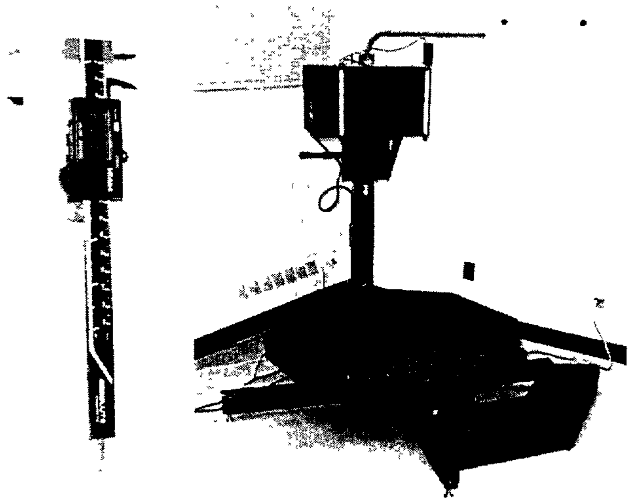

Fig 1 Digital caliper (probe) and laser head scanner

2.2 Subject selection

Subjects were selected from a population of volunteers in such a way as to sample throughout a 98% enclosing boundary of the bivariate distribution of head breadth and head length. The selection of the representative test sample was made on the basis of the two following assumptions:

1. Head length and breadth are the main critical variables for ballistic helmet fit, and
2. Subjects of similar head length and breadth dimensions (similar meaning within ± 5 mm of each other) will produce similar standoff distance results.

By definition, a critical variable is a limiting one, i.e. one for which not all of the population is accommodated. The problem in selecting a sample that is representative of the population is that the critical variables cannot be determined until after the fit testing is performed. The first assumption was made on the basis that head length and breadth are commonly used as helmet-fitting variables, along with head circumference, and were likely to be limiting variables for the helmets under consideration (i.e. army-type suspension helmets). They are also virtually orthogonal variables (Pearson r of 0.10), which means that very little of the information provided by one variable is contained in the other. Head circumference was not considered explicitly because it is not independent of the other two; it can quite accurately be determined from the other two dimensions (multiple R of 0.90) and therefore provides very little additional information. In the event that other variables would turn out to be critical after analysis of the results, another representative sample would have to be drawn from the population for further tests.

The main purpose of the second assumption is to allow the investigators to reduce the sample size and make parsimonious use of subjects and resources. Although the size of the subject selection grid, or the interval between successive head dimensions, is arbitrary, it should be fine enough to allow inferences about the percentage of non-accommodated individuals in the population of interest. In these experiments, a sample of 30 subjects was deemed to be a good compromise between the cost of testing and population representation.

Fig. 2 illustrates the distribution of the test subjects among the subject pool. A 98% equiprobability ellipse is shown for both males and females, representing the desirable accommodation envelope. A uniform spacing of 5–10 mm between test subjects was aimed for, and achieved for the most part. This resulted in 30 subjects being required to represent the population based on head length and breadth.

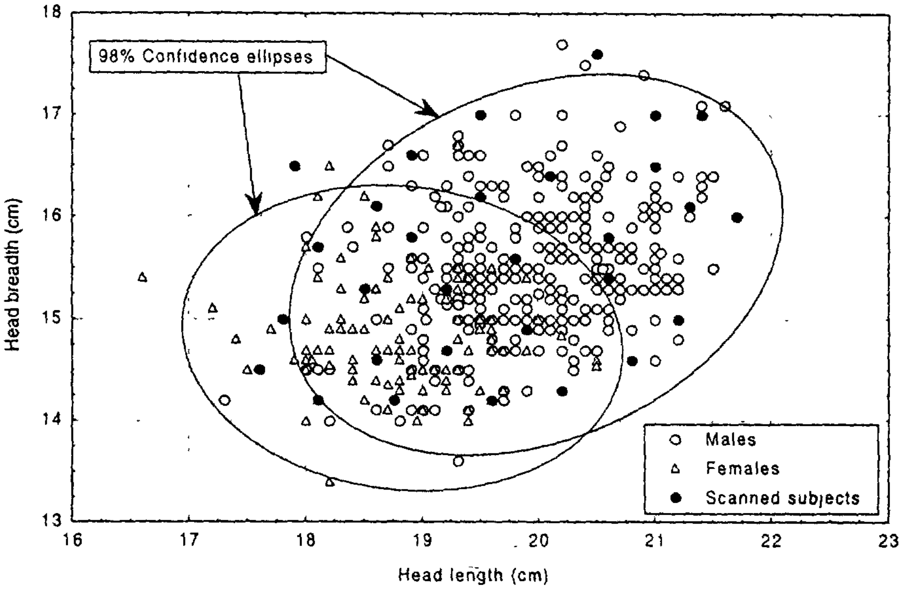

Fig. 2 Scanned subjects relative to sample distribution.

2.3 Scanning test protocol

Prior to scanning, 19 facial landmarks were identified and marked on each subject. The subjects were then fitted with a thin (0.5 mm) latex scanning cap, contoured around the ears. Because the laser scanner is unable to collect data from surfaces parallel to the laser beam (the top of the head) each subject was scanned twice: once with their head in the upright position, and once with their head tilted forward. The 3D data from both scans were later merged into one complete scan of the head to provide one of the files required for the analysis. Helmets were also scanned upright and tilted forward in order to create a complete helmet file. Subjects were issued a helmet size in accordance with the manufacturer's guidelines and instructed to properly adjust their helmet. Once the helmet was fitted, a final scan was taken that captured the relationship between the fitted helmet and the head. The scanning protocol resulted in three datafiles that were to be used in the standoff distance analysis phase.

(a) a subject file;
(b) a helmet file;
(c) a helmeted subject file.

2.4 Probe test protocol

The probe test consisted of measuring the distance from the outside surface of the helmet to the subject's head. This was done by inserting the depth- measuring blade of the digital caliper (Fig. 1) through holes drilled in the helmet. Thirteen holes were drilled in an asterisk pattern as shown in Fig. 3 to cover the entire surface of the helmet. In this test, the distances obtained include the thickness of the helmet, which was 10 mm. (Insert Fig. 3 about here)

A total of nine subjects (from the group of 30) were selected along the major and minor axes of the equiprobability ellipse shown in Fig. 2. After donning the drilled helmet, the standoff distances were measured with the probe. The probe depth from the outer surface of the helmet was recorded when the subject reported feeling the probe contact their head. The subjects were then immediately scanned with the laser scanner.

The accuracy of this method can be affected by the position or inclination of the caliper relative to the hole as well as by the pressure exerted by the probe as it contacts the scalp of the test subjects. In this method, it is important to avoid displacing the helmet during measurement, which could bias the results. Care was taken to insert the digital caliper perpendicular to the surface of the helmet at in each of the 13 holes, and to apply the same pressure on the caliper during measurement, without displacing the helmet. Repeatability tests, where 10 identical sets of measurements were made on a single individual, showed that the 10 distances obtained using the probe were within ± 0 60 mm of the mean, 95% of the time

2.5. Analysis

Using Shapeanalysis, the three datafiles were cleaned of spurious data. The subject scan (a) and the helmet scan (b) were placed appropriately relative to one another, using the helmeted head scan (c) as a positioning template. Registration of the three scans was done visually by the operator. Since the standoff distance analysis requires the inside of the helmet, the measures taken to the outer

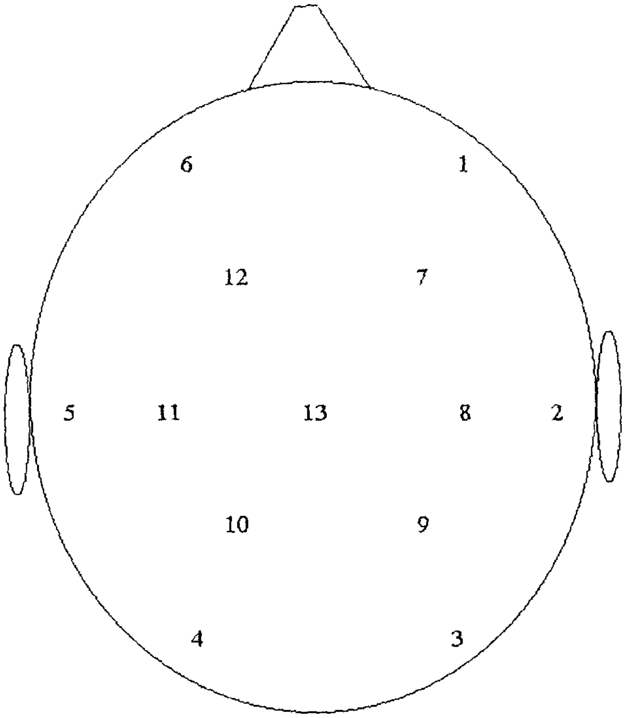

Fig. 3. Pattern of holes drilled through the helmets for probe measurement.

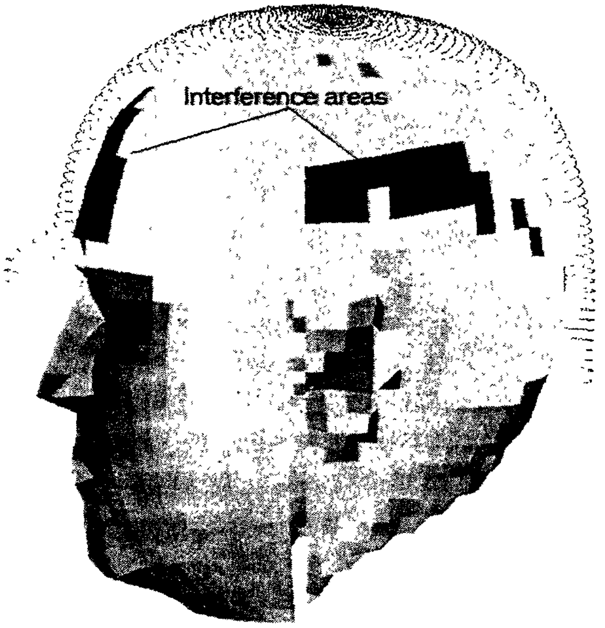

Fig. 4. Results of a typical standoff distance analysis showing the inside surface of the helmet in relation to the subject's head. Standoff violation areas shown in dark zones.

surface of the helmet were reduced by a distance equivalent to helmet thickness. This was done with the help of a polar scaling function specifically developed for this application (Beecher, 1993). This new surface measurement was used for the remainder of the analysis.

The helmet accommodation module was used to calculate the minimum distance between the head and helmet surfaces. The distances were color coded to help visualize the extent and severity of the interference areas. Fig. 4 shows the results of the analysis of the results from subject 1. The head and the inside surface of the helmet (dots) are shown along with dark areas representing zones of non-compliance with the requirements.

In the scanner-probe comparison, a slightly different method was used. Scanning and datafile merging remained the same, but the polar scaling function was not required. Also, since the standoff distances of the 13 specific locations on the helmet were to be compared with the laser measurements, the procedure involved two additional steps: the identification of each of the 13 probe holes on the scans, and the calculation of the minimum distance at those points. The 13 holes were located visually by the computer operator from each scan. By using one of the features of Shape analysis, the x, y, z coordinates of the hole locations on the helmet surface were found and recorded. The standoff distance for each point was obtained by cross-referencing with the output file of the helmet accomodation module, using the co-ordinates as the search key.

3. Results

3.1. Helmet sizing assessment results

The results of the helmet accommodation module were displayed graphically on-screen as well as in a text file containing the list of approximately one thousand sets of x, y, z co-ordinates and standoff distances. Fig. 4 shows the final graphical output of the standoff distance analysis module. The minimum distances are displayed in color-coded zones. In this black and white picture, the darker zones represent areas where the helmet surface interferes with the minimum standoff distance of 12.5 mm. The graphical representation provided by the software is of tremendous value for the interpretation of the results. It can also serve to convince designers of the need to modify the shape or size of the helmet, and in which areas.

The data generated in the standoff distance analysis were summarised further by integrating the standoff results over the surface of the head covered by the helmet. A percentage was obtained by dividing the interference area by the total area which represented an overall non-compliance assessment. The results are listed in Table 1.

3.2. Probe versus scan data results

A paired t-test was performed on the overall results comparing individual sets of the mean standoff distances obtained with both methods for all hole locations. The test indicated that the methods differed significantly

Table 1
Standoff analysis summary results

Subject	Head length (cm)	Head breadth (cm)	Head circumference (cm)	Gender	Helmet size	% area below requirement
1	21.4	17.0	62.5	m	L	4.4
2	20.6	15.4	58.2	m	L	0.3
3	20.8	14.6	57.2	m	L	0.0
4	19.5	17.0	58.5	m	L	0.0
5	18.8	14.2	55.3	f	M	0.0
6	20.6	15.8	58.5	m	L	0.0
7	20.1	16.4	59.3	m	L	0.0
8	19.2	14.7	54.6	f	M	0.0
9	18.9	16.6	58.0	m	L	0.0
10	21.0	16.5	59.8	m	L	0.0
11	19.5	16.2	58.5	m	L	0.6
12	19.2	15.3	55.5	m	M	0.0
13	19.9	14.9	57.2	f	M	1.8
14	21.7	16.0	59.5	m	L	0.1
15	21.3	16.1	60.8	m	L	4.2
16	20.2	14.3	56.4	m	M	4.2
17	21.2	15.0	58.0	m	L	8.4
18	17.9	16.5	56.0	f	M	14.8
19	19.8	15.6	58.9	m	L	0.0
20	21.0	17.0	60.9	m	L	4.7
21	18.9	15.8	55.8	m	L	0.7
22	18.5	15.3	54.1	m	M	0.0
23	17.8	15.0	53.9	f	M	0.0
24	17.6	14.5	51.8	f	M	0.0
25	18.1	15.7	55.6	f	M	0.0
26	19.6	14.2	56.2	f	M	6.8
27	18.6	14.6	54.2	f	M	0.0
28	18.1	14.2	52.8	f	M	0.0
29	18.6	16.1	55.3	f	M	1.4
30	20.5	17.6	60.5	m	L	0.2

Table 2
Comparison of mean probe and scanner distances for nine subjects (mm). Distances include the thickness of the helmet (10 mm)

Measurement location	Probe		Helmet accomodation module	
	Mean	sd	Mean	sd
1	32.1	04.2	27.7[a]	05.3
2	26.1	06.4	27.0	07.3
3	30.5	02.7	26.5	05.6
4	30.0	02.0	25.3	08.4
5	27.2	05.1	26.3	05.1
6	32.4	04.1	27.8[a]	06.5
7	36.9	03.5	28.5[a]	06.9
8	34.8	03.9	29.3[a]	02.8
9	32.5	03.0	27.9	06.5
10	31.4	03.3	27.4	06.4
11	32.2	04.5	27.4[a]	04.6
12	37.4	03.7	29.4[a]	05.6
13	29.2	03.7	25.3	06.4
Overall	31.7	05.0	27.4[a]	05.9

[a] Significantly different from probe, $p < 0.05$

(t-value $= 7.84$, $p < 0.001$). Table 2 shows the results of paired t-tests done on a hole-by-hole basis. Systematic differences were found in six of the 13 holes (significant differences are denoted by asterisk marks in Table 2). It is interesting to note that these six holes are symmetrically located in the frontal half of the helmet; holes 6, 12 and 11 are the left side opposites of holes 1, 7, and 8, respectively (see Fig. 4).

Fig. 5 shows the difference between the probe and scanner results relative to their location on the helmet

4. Discussion

4.1. Helmet sizing assessment

The helmets under evaluation were issued to individual participants in the study on the basis of guidelines furnished by each of the manufacturers. Some manufacturers recommended issuing helmets based on head circumference, while others used a combination of head length, breadth and circumference. Fig. 6 shows the results of the helmet standoff analysis for the 30 test subjects in relation to their head length and breadth. Each point on the graph represents an individual. Gray or black data points on the graph represent significant non-compliance or violation. Three categories emerged from the analysis: no violation, minor violation, and substantial violation. Minor violations of the minimum standoff distance were those exhibiting a small degree of interference over a small proportion of the head area (less than 2%). Substantial violations were those exhibiting significant interference (several millimeters) over a larger area of the head (greater than 4%).

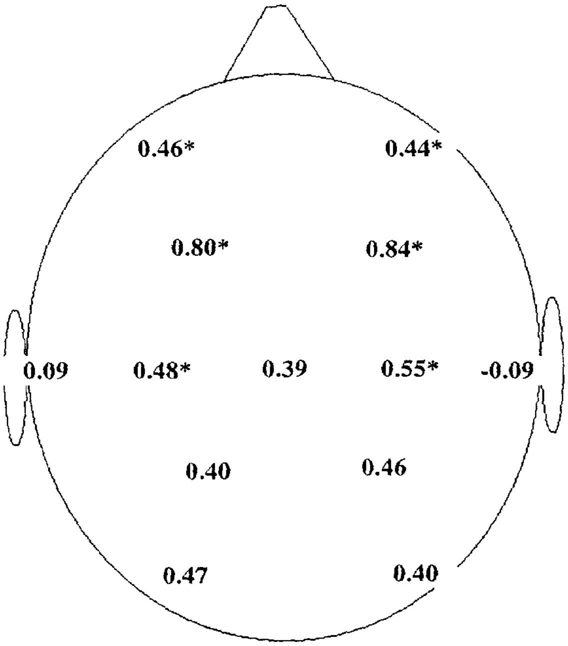

Fig. 5 Average difference between probe and scanner measurements (cm). Significant differences are marked by an asterisk.

A number of observations can be made from Fig. 6. Firstly, an oblique line can be drawn which separates the medium and large helmet wearers. This reflects the use of head circumference as the basis for issuing the helmet, and is not surprising since head circumference can be obtained by a linear combination of head length and head breadth with a multiple *R* of 0.90. Secondly, three distinct zones can be identified where the more severe violations occur: one is at the upper end of head length for the medium helmet, another is at the upper end of head length for large helmet wearers, and a third is at the upper end of head breadth for the medium helmet. Violations seem to correlate quite well with head length and breadth. This appears to confirm the earlier assumption that these two dimensions would be critical for fit. Clear helmet size cut-off criteria become evident from Fig. 6: a limit of 19.5 cm in head length can be seen for the medium helmet, and one of 21 cm for the large helmet. This shows that proper issuing of the helmet would have to rely on head length and breadth rather than on circumference.

Fig. 7 illustrates the kind of sizing limits that would be required. The suggested cut-off limits would, in all likelihood, have avoided the problems encountered with a few of the subjects wearing the medium helmet, since they would have been given a larger helmet. Similarly, most of the large helmet interference cases would probably have been eliminated had there been an extra-large helmet available.

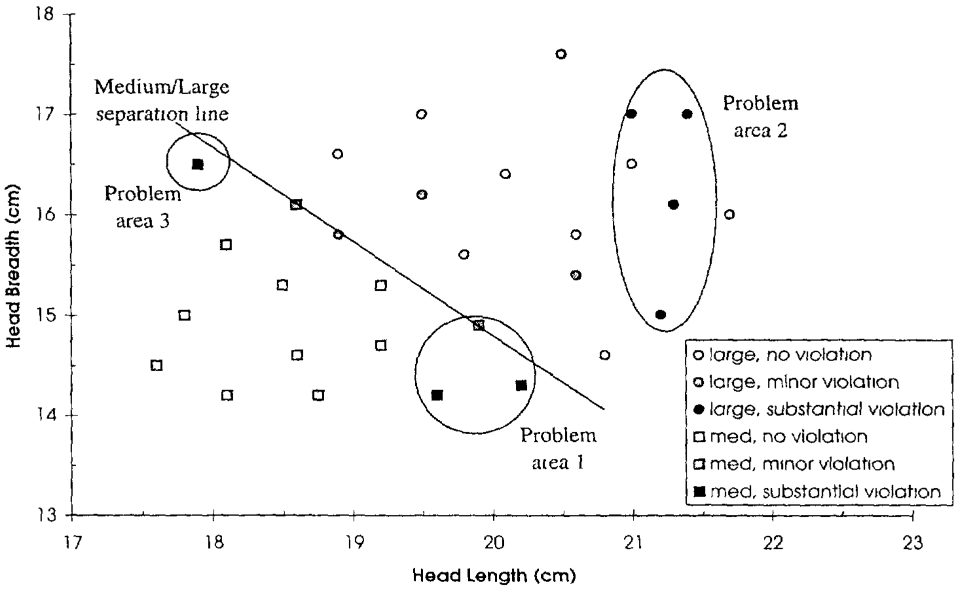

Fig 6 Overall results of standoff distance analysis

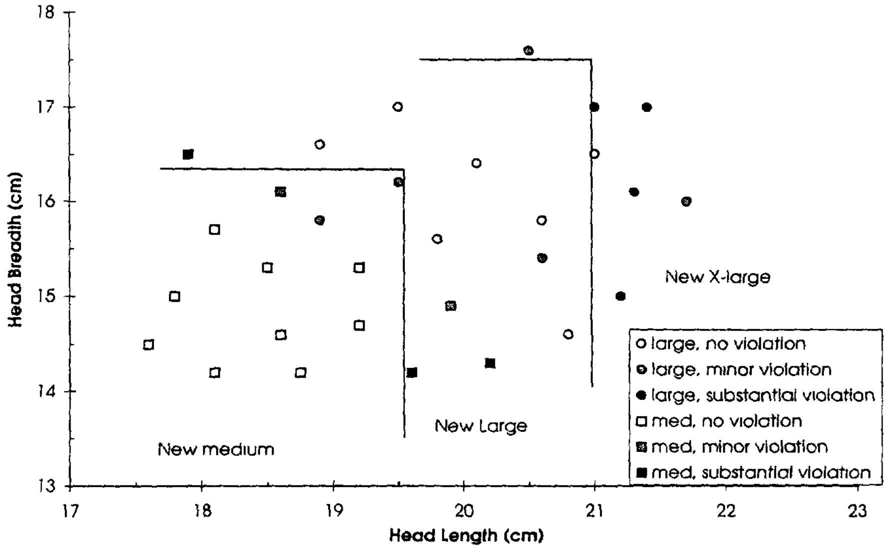

Fig 7. Suggested helmet sizing criteria derived from standoff distance analysis

The information generated in the analysis was useful in several ways. On the one hand, it provided a good first-order approximation of population accommodation given a helmet system, and on the other it was able show where transitions should occur from size to size. In the above example, the analysis indicated a need for a larger sized helmet and the need to change the sizing/issuing criteria.

4.2. Probe versus scan data

The difference between the probe method and the scanning method was sizable, given the accuracy of both measurement tools. On average, the probe distance tended to be about 4 mm longer than the comparable measurement taken by the scanning method. Inherent differences in the two methodologies make it difficult to draw conclusions on which of the two provides the truest measure of standoff distance, but a review of sources of error in each case can provide insight into the reasons for the discrepancy

The accuracy of the standoff distance measurements made from laser scans is affected by various factors The first and most fundamental one relates to the resolution and repeatability of the scanner itself. Using 0.08 mm as the 95% random error interval for the scanner, the use of two scans might create a 95% uncertainty interval of ± 0.12 mm for standoff distance results, which is minimal compared to the absolute discrepancy measure. A second source of error can come from the positioning of the head and helmet scans relative to each other in the 3D data editing software. The positioning of the helmet and head using the helmeted head as a template was easily done using the 3D editing software, and the error introduced in this part of the analysis process is expected to be small.

The principal sources of error, i.e the ones that could account for most of the discrepancy, appear to be related to the constraints imposed by the scanner itself (scanning cap) and of the length of time it takes to complete a scan (involuntary head movements during scanning). The scanning cap has a direct effect on the standoff distance measurement because it increases the volume of the head by its thickness and that of the hair within it. Since scanning caps tend to not conform perfectly to the underlying cranium, because of pockets of trapped air and ripples, the overall thickness is even greater. The scanning cap used in this study was 0.5 mm thick latex rubber Hair thickness (perfectly compressed) will vary depending on the subject, but it is of the order of one or two mm. Since the scanning cap did not perfectly compress the hair in all areas, additional space was taken up. It is difficult to estimate the overall thickness of the cap and hair because it varies between individuals and because it cannot be measured directly· subjects would need to be scanned twice: once with hair and a second time with their head clean shaven. However, the effect of cap and hair is probably of the order of 2–3 mm, i.e. a major portion of the difference between the two methods

Although every effort was made to minimize the effect of subject movement during scanning, it was impossible to eliminate it completely with the methodology used. Subjects were told to hold still and given a reference point to help them remain stable,. However, this turned out to be very difficult to achieve for many subjects during the 20 s scanning period (especially when the scanning head travels in and out of the subject's field of view). Scans were verified for head movement immediately after completion. If there was a significant mismatch between the start and the end of the scan, i.e. more than 1 mm or so, the scanning session was repeated. However, this verification method is somewhat flawed since it will only pick up cases where the head positions differed at the start and end of the scan. Minor head movements in the mid portion of the scanning are not identifiable on a scan. Thus, there was no real way of certifying that a subject did not move during any portion of the 20 s scanning process other than the first and last few scan profiles. Since two scans were made of each subject (with and without a helmet), slight head movement in both scans can make it slightly more difficult to position the head scan for the standoff distance analysis.

One of the main reasons for the discrepancy observed between the two methods is intrinsic differences in the methods of operation of the measuring devices. The scanner is a surface-measuring device requiring light-coloured matte surfaces (hence the use of a scanning cap), while the probe is a physical measuring device relying on physical feedback from a solid surface. Therefore, the first difficulty comes from the fact that the two devices measure two different things. The scanner measures the distance between the surface of the scanning cap and the outside of the helmet, whereas the probe measures the distance between the subject's scalp and the outside of the helmet.

One of the advantages of the scanning method is that the shortest distance between the helmet and the head is easily found. In the probe method, the measurer's subjective orientation of the depth gauge does not guarantee that the shortest distance is measured every time. Thus, a positive bias can be expected from the probe method that could also explain some of the observed differences. Areas where distance results are sensitive to probe orientation, i.e. in areas where the shape of the helmet and the head diverge, would be prone to larger biases. Such is thought to the case for holes 1, 6, 7, 8, 11, and 12.

As regards helmet standoff distance calculation, the two main difficulties encountered in these experiments can be mitigated, if not eliminated, through improvements to the methodology. For instance, tight-fitting spandex scanning caps could be used instead of the thin latex rubber ones. Although they are thicker than the paper-thin latex caps used in these experiments, their compressive power and adaptability to the head's morphology is such that their use would result in a more uniform combined hair and cap thickness across subjects. Once established as relatively constant, this thickness could then be subtracted from the standoff measurements. The problem of involuntary head movement during scanning, assuming scanning times cannot be reduced significantly, could be mitigated by the use of a head rest or a bite bar. With the implementation of those changes, it is thought that the scanning method accuracy could approach the levels that the instrument is capable of, i.e. in the 0.2–0.5 mm range. This would make it far superior to the probe method in terms of accuracy and richness of data.

5. Conclusions

Three-dimensional laser head scanning offers unparalleled richness of data and analytical power in the calculation of standoff distance. When combined with a representative sample of the user population the laser head-scanning method can provide a compelling assessment of a helmet sizing system. It can help designers visualize how individuals wear the helmet and pinpoint the location of problem areas. The 3D data can be used to reshape the helmet shell, reposition it relative to the suspension system, and resize it to fit the population.

Although the laser scanner provides sub-mm accuracy, the use of a scanning cap and head movement during scanning can introduce bias in the computation of helmet standoff distance. Shaven or bald heads are ideal for this type of analysis, but failing that the use of tighter-fitting scanning caps would represent an improvement. Also, particular attention should be paid to head stabilisation during scanning. The use of a head support or a bite bar would be beneficial.

Overall, 3D-laser head scanning combined with a systematic selection of test subjects proved to be an excellent method of assessing population accommodation to helmets. Some of the benefits included the easy identification of areas of non-compliance and visualisation of the extent and severity of the violations of the minimum standoff distance.

Acknowledgements

The authors would like to thank the two anonymous referees for their thoughtful comments and suggestions. They were much appreciated.

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