

Assessment of the ergonomic design of self-contained self-rescuer (SCSR) devices for use by women in mining

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Increasing numbers of women are entering the South African mining industry (SAMI), but self-contained self-rescuer (SCSR) devices might not be suited to female anthropometric dimensions. The aim of this project was to assess the ergonomic design of SCSRs for use by women in the SAMI. Body measurements and questionnaires were collected from 100 female mine workers from one coal, one platinum and one gold mine in South Africa. Practical performance assessments of SCSRs when worn on the belt and when donned and in use were conducted with 11 female mine workers in a simulated underground mining environment. The majority of the participants experienced pain or discomfort when wearing an SCSR and numerous anthropometric dimensions differed from reference values. Dimensional limitations or short-comings of current SCSRs for use by women in mining were identified. The study findings can be used to inform interventions to improve the design and fit of SCSRs.

INTRODUCTION

Body-worn self-contained self-rescuers (SCSRs) are part of the personal protective equipment (PPE) required in coal mines and high-risk areas in hard rock mines (SANS1737:2008; Schreiber, 1999). These devices are designed to be worn on the body for the complete duration of a working shift (SANS1737:2008; Schreiber, 1999). They are used in case of emergency situations, such as fires or gas inundations, to protect the user from contaminants in the ambient air and to provide breathable air for a sufficient amount of time to allow the mine worker to escape from the mine (Kowalski-Trakofler *et al.*, 2008; Sandström, 2015; Schreiber *et al.*, 2003; Schutte *et al.*, 2005; Teeravarunyou, 2008). Schreiber and Sehlabana (2015) reported that there were four makes of SCSRs deployed in the South African mining industry (SAMI). The rated durations of these devices range from 25 to 40 minutes, the weights of the unopened units range from 2.1 kg to 2.5 kg, and the average heights, widths and depths of the units were 202 mm, 185 mm and 104 mm, respectively (Afrox, 2014; Drägersafety, 2010; MSA, 2016; Schauenburg Lighting Technologies, 2013). Some of the side-effects of wearing SCSRs include discomfort, restriction of movement and physical load (Bakri *et al.*, 2012; Coca *et al.*, 2011; ISO/TS 16976-8:2013; Zungu, 2012).

Although the mining industry is historically male-dominated, there has been an increase in the number of women entering the SAMI as a result of regulations such as the Mining Charter and the Minerals and Petroleum Resources Development Act 28 of 2002 (South Africa, 2002a and 2002b; Zungu, 2012). Women have different anatomical and physiological characteristics than men (van Aardt *et al.*, 2012; Zungu, 2013). However, PPE has generally been designed based on male anthropometric dimensions (AngloAmerican, 2012; van Aardt *et al.*, 2008; Zungu, 2013).

As a result, women's comfort, safety and performance at work may be compromised (van Aardt *et al.*, 2008; Zungu, 2012). Further research on the compatibility of PPE, including SCSR devices, for use by women in mining is therefore warranted.

The implementation of ergonomics principles during the design and manufacture of any article for use at a mine is mandated in the Mine Health and Safety Act (Act 29 of 1996) (South Africa, 1996). The goal of ergonomics is to ensure that tasks, jobs, products, machines, equipment, environments and systems are suited to people in order to improve their health, safety, productivity and well-being (International Ergonomics Association, 2016; ISO/TS 16976-8: 2013; Schutte, 2005; Schutte and James, 2007; Schutte and Shaba, 2003). Anthropometry is a branch of ergonomics, and refers to the scientific procedures and processes of acquiring surface anatomical dimensional measurements such as lengths, breadths, girths and skinfolds of the human body by means of specialist equipment (Stewart *et al.*, 2011). Anthropometric data are required for the appropriate design of SCSRs (ISO/TS 16976-2: 2015; Schutte and Shaba, 2003). The aim of this study was to assess the ergonomic design of SCSR devices for use by women in the SAMI, in order to identify improvements that would make the wearing of SCSR devices more acceptable, comfortable for the wearer, and not impede escape. This paper was derived from the report for a study commissioned by the Mine Health and Safety Council (project number: SIM 160902, Hodgskiss *et al.*, 2017).

METHODS

This project employed mixed methods as both qualitative and quantitative data were collected. The research was cross-sectional, and data collection took place between February and April 2017. The research comprised two components, namely an anthropometric assessment of women working at mines in South Africa and a practical ergonomics performance assessment. Ethical approval to conduct this research was obtained by the CSIR Research Ethics Committee (Ref: 179/2016).

The anthropometric assessment took place at one coal, one platinum, and one gold mine in South Africa. A total of 100 female mine workers participated. Anthropometric measurements were taken from 27 body sites according to the International Society for the Advancement of Kinanthropometry (ISAK) standards (Stewart *et al.*, 2011). In addition, body mass index (BMI) and waist-to-hip ratio were calculated. The identified measurements were selected primarily with reference to ISO/TS 16976-2:2015 (Part 2) and ISO/CD 16900-5.2 (Part 5). Participants also completed questionnaires to provide information on demographic characteristics and subjective responses relating to the comfort of SCSRs. Researchers fluent in local languages were available to assist the participants.

The practical ergonomics assessment involved an analysis of the use of approved SCSRs by women in the SAMI when navigating a test route. The study sample comprised of 11 female mine workers, who usually worked underground and were required to wear SCSRs for their daily work. Six of the participants worked at a metalliferous (platinum) mine and five worked at a coal mine. The study was undertaken in a simulated underground mining environment, as per sub clause 5.2.9.1 of SANS 1737:2008. The participants were required to complete a predetermined test route that involved upright walking on level and sloped surfaces, stooped walking, crawling, and going up and down stairs. A control session involved the participants having to navigate the route while wearing normal PPE, but without an SCSR. Testing sessions involved navigating the route wearing each of four approved SCSR models on the belt and while donned and activated. Prior to testing, the correct procedures for opening, donning and using each make of escape apparatus were demonstrated in accordance with the manufacturer's instructions for use. Data collected included environmental temperature, oral body temperatures, test duration, ratings of perceived exertion (RPE) (Borg, 1962) and body discomfort (Corlett and Bishop, 1976). The ergonomic assessment questionnaire as included in SANS 1737:2008 was completed, and observations and photographic recordings were also made.

Data were captured electronically and analysed. Descriptive and comparative statistical analyses were performed on the quantitative data, and statistical significance was set at 95% ($p < 0.05$). Averages,

standard deviations (SDs), minimum and maximum values, and percentiles were determined for each anthropometric variable, which were compared against ISO reference values, using the one-sample Median Test. For the practical ergonomic assessment, comparisons were made of responses obtained during the control session, when the units were worn on the belt, and when donned and in use. Comparisons of responses while using the different SCSR models were also made.

RESULTS

Anthropometric assessment

Demographic information and comfort ratings were gained from questionnaires completed by 91 of the participants. The average age of the participants was 34.9 (SD: 7.5), ranging from 19 to 57 years. Most of the participants were South African (95%) and 98% were Black. Almost all of the participants (99%) considered the SCSR devices to be too heavy, and 92% reported that they disturbed their work.

The majority of the participants reported discomfort while wearing SCSRs on the belt during their daily work, with 68% reporting that this occurred most or all the time (Figure 1). The body areas where the most discomfort was experienced were the lower back, hips, and stomach (abdomen) (Figure 2). Participants commented that they hoped the SCSRs could be made smaller, lighter, and more comfortable.

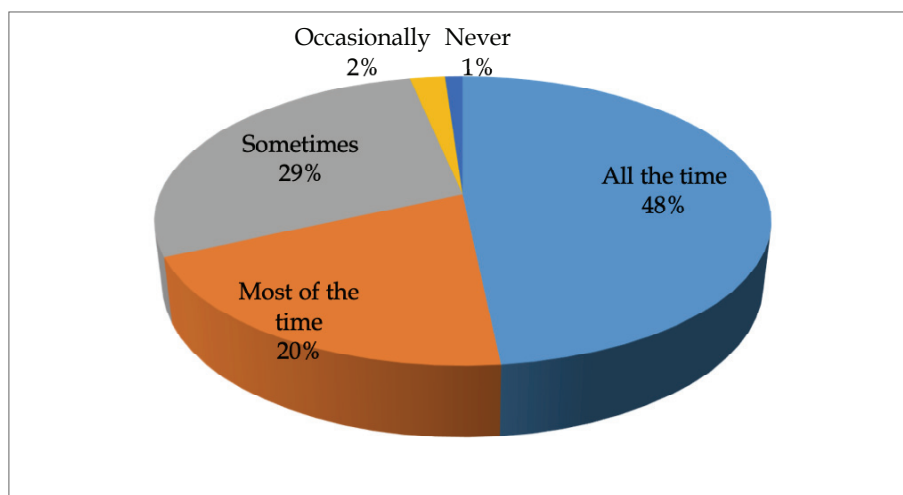


Figure 1. Frequency of pain or discomfort when wearing an SCSR.

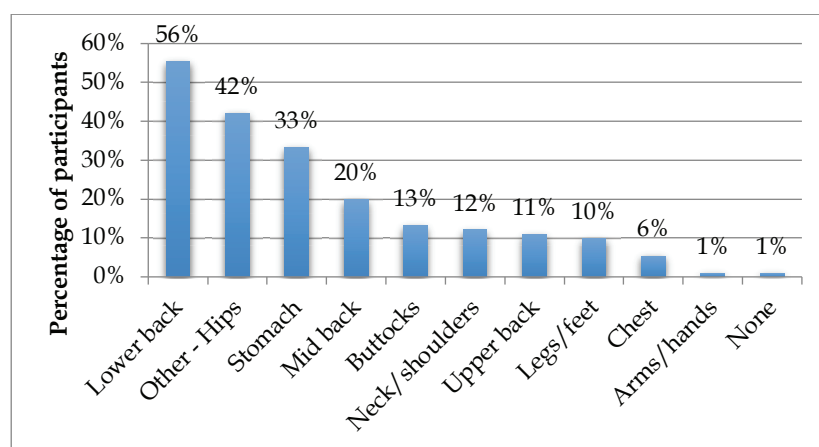


Figure 2. Area of body with pain or discomfort when wearing an SCSR.

Anthropometric measurements were obtained from 98 participants. Anthropometric data, including the average, SD, and 5th, 50th and 95th percentiles, for the 27 measurements as well as the derived indices of BMI and waist-to-hip ratio is shown in Table 1. The data were compared with torso reference values from ISO/CD 16900-5.2 and ISO/TS 16976-2:2015 for males and females, and for females only, to assess whether the data used for design and testing of SCSRs were suited to women in the SAMI. Numerous significant differences were evident (Table 1). As expected, most of the reference values, such as for height measurements, were larger than the average measurements from our study, as our study only included female participants. The measurements for which the study sample had higher averages than the reference values were for head circumference, nose breadth, chest circumference, waist breadth, waist circumference and hip circumference, along with BMI and waist-to-hip ratio.

Table 1. Anthropometric data for the study sample compared with reference and previous study data.*

	Measurement	N	Study data							Reference data	
			Average	Standard deviation	Minimum	Maximum	5 th percentile	95 th percentile	50 th percentile	ISO data 50 th percentile (males and females)	ISO data 50 th percentile (females only)
1	Stature (cm)	98	160.2	5.6	147.1	172.4	150.8	168.4	160.4	169.1	162.7
2	Weight (kg)	98	76.3	15.3	49.2	121.2	52.8	101.5	75.9	80.3	72.1
3	Sitting height (cm)	93	81.6	3.1	74.9	90.3	77.0	86.9	81.5	-	-
4	Head circumference (cm)	90	58.2	3.3	52.0	69.5	53.6	63.7	57.7	56.5	55.5
5	Neck circumference (cm)	90	33.2	1.9	29.0	38.4	29.9	36.2	33.2	36.9	33.5
6	Head length (cm)	91	19.1	2.0	12.7	23.2	14.0	21.5	19.4	19.2	18.7
7	Maximum head breadth (cm)	92	13.7	1.7	8.9	17.1	9.8	15.7	14.0	15.0	14.6
8	Menton-sellion length (cm)	88	11.0	0.6	9.5	12.4	10.1	11.9	11.0	11.8	11.3
9	Interpupillary distance (cm)	92	6.2	0.5	4.6	7.5	5.3	6.8	6.2	6.35	6.2
10	Eye-to-nose diagonal (cm)	91	4.5	0.9	2.8	7.6	3.4	6.0	4.4	-	-
11	Nose breadth (cm)	91	4.0	0.3	3.0	4.7	3.4	4.5	4.0	3.45	3.3
12	Top of breastbone to centre of mouth (cm)	91	13.0	1.7	8.4	16.8	10.4	16.0	13.0	-	-
13	Height of prominent neck vertebra, sitting (cm)	87	60.4	2.7	55.2	66.6	55.9	64.6	60.2	64.8	62.8
14	Shoulder (acromion) height, sitting (cm)	87	53.9	2.8	48.4	62.2	49.8	59.3	53.8	58.7	56.9
15	Mid-shoulder height, sitting (cm)	87	39.6	3.2	33.9	55.7	35.1	44.8	39.8	60.6	57.9
16	Shoulder breadth (deltoid) (cm)	87	42.3	3.0	36.3	51.9	37.5	46.7	42.2	43.7	41.6
17	Chest breadth, at level of nipples (cm)	87	29.5	2.9	22.9	37.2	25.6	35.4	29.2	30.6	28.2
18	Chest depth (cm)	87	23.0	3.6	17.2	33.6	17.8	29.4	23.0	25.0	25.1
19	Chest circumference (cm)	87	99.9	11.2	78.6	126.5	85.0	120.2	99.8	91.9	92.1
20	Trunk height to the top of the breast bone, sitting (cm)	92	54.4	2.9	48.5	61.8	49.4	59.2	54.3	58.5	57.3
21	Height of maximum lumbar curvature, sitting (cm)	92	21.4	5.2	11.2	34.1	13.3	29.2	20.8	23.7	23.2
22	Sitting hip height (cm)	92	22.1	2.5	13.5	29.1	18.7	26.6	21.8	-	-
23	Lower abdominal depth (cm)	92	25.3	5.2	15.9	37.7	17.8	33.2	24.3	26.7	25.0
24	Waist breadth (cm)	92	30.5	4.5	20.1	43.2	24.2	38.3	30.0	26.2	26.4
25	Hip breadth (cm)**	92	33.9	5.8	22.9	63.3	26.0	41.5	33.8	32.4	32.1
26	Waist circumference - natural indentation (cm)	96	84.7	11.8	52.5	107.6	67.1	103.0	84.8	80.4	76.9
27	Mid-hip circumference (cm)	96	110.5	11.9	83.1	145.0	92.2	130.3	110.5	105.8	105.6
28	BMI (kg/m ²)	98	29.8	5.8	19.9	43.7	21.4	39.9	29.6	23.7	22.2
29	Waist-to-hip ratio	96	0.77	0.07	0.42	0.94	0.67	0.88	0.77	0.76	0.73

* Highlighted values indicate significant differences (p<0.05).

**Different anthropometric landmarks were used between studies for measuring hip breadth.

Practical performance assessment

The use of SCSR devices by women in the SAMI was assessed in a simulated underground test route. The average age of the 11 participants was 31.1 years (SD: 4.4, range: 26 – 41), the average stature was 163.5 cm (SD: 4.3 cm, range: 157 – 171 cm), and the average weight was 76.9 kg (SD: 17.4 kg, range: 62 – 121 kg). The average time taken to navigate the test route with the SCSR worn on the belt was 10 min 15 s, and 10 min 52 s while donned and in use. The average time to complete donning and adjusting the units was 2 min 32 s, which was longer than expected.

Ratings of perceived exertion (RPE) and body discomfort were provided by the participants. The RPE scale ranges from 6 ('very, very light') to 20 ('very, very hard') for both central (heart and lung) and peripheral (muscular) exertion. Greater exertion was evident when an SCSR was worn on the belt than when no SCSR was worn, and the highest levels of exertion were evident when the SCSRs were donned and in use (Figure 3).

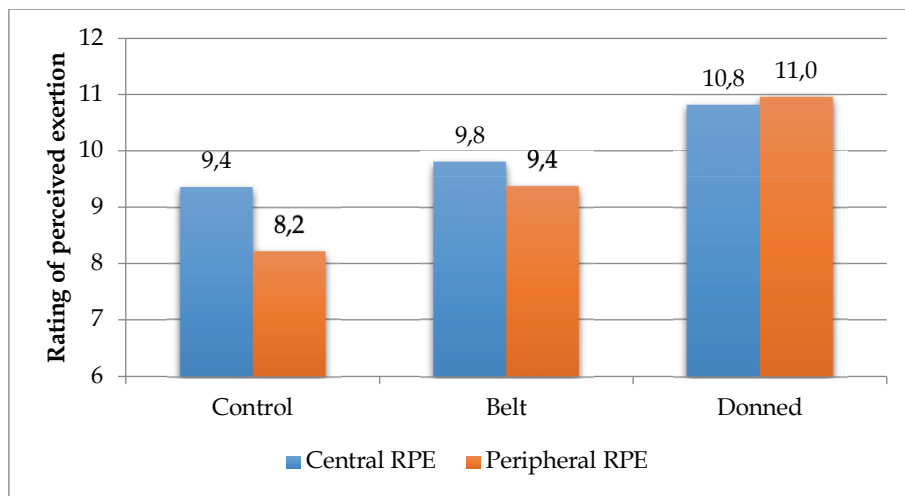


Figure 3. Central and peripheral ratings of perceived exertion (RPE).

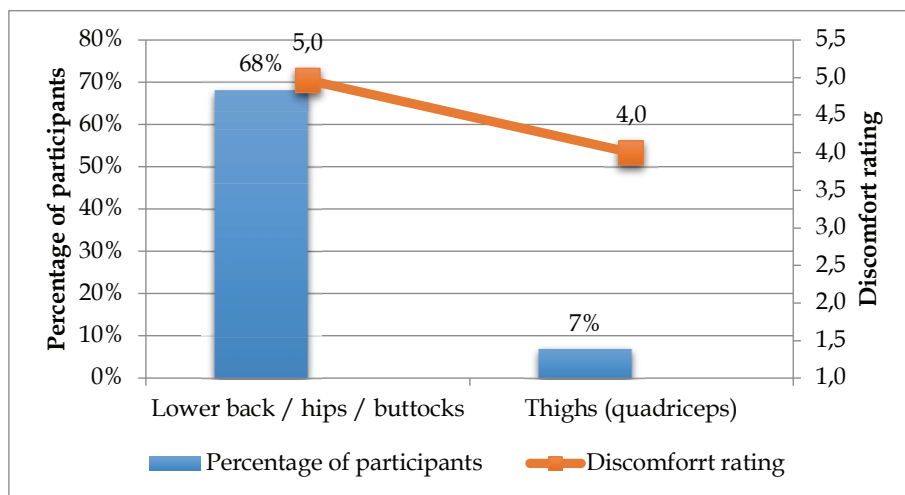


Figure 4. Body discomfort while wearing SCSRs on the belt.

A body discomfort map was used on which participants indicated where they felt discomfort, along with the level of discomfort experienced for each area, on a scale from 1 ('very slight discomfort') to 10 ('extreme discomfort'). None of the participants reported discomfort after completion of the control route. Discomfort while the units were worn on the belt was mainly experienced in the lower back, hips

and quadriceps (Figure 4). The highest comfort ratings for wearing the units on the belt were reported for the units that were smaller, lighter and contoured to fit the wearer’s body. When the units were donned and in use, the participants experienced discomfort mostly in the neck, shoulders, jaws, teeth, throat and chest (Figure 5). The participants experienced the highest levels of neck and jaw strain when a model that was worn on the head rather than on the chest was donned.

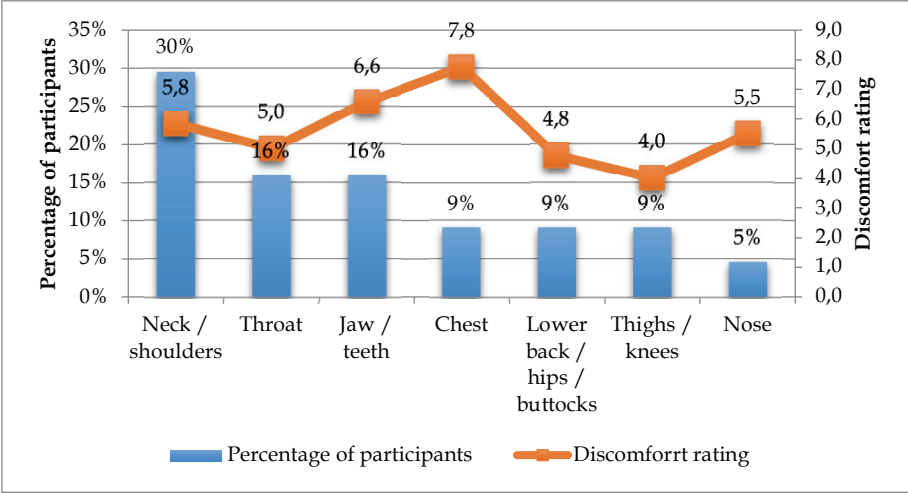


Figure 5. Body discomfort while SCSRs were donned and in use.

The participants completed an ergonomic assessment questionnaire to rate the SCSRs on various aspects on a scale from 0 (‘totally unacceptable’) to 10 (‘highly acceptable’). The average scores for the main categories of ‘ergonomic design for normal wearing’ (i.e. wearing the SCSR on the belt), ‘ergonomic design for donning’, and ‘ergonomic design for negotiating escape routes’ are shown in Figure 6. Although these average scores were considered acceptable (a score of 5 or above), the average scores for some of the SCSR models were 5 or below, and there was variability in the responses between participants. The average scores for each question are shown in Table 2.

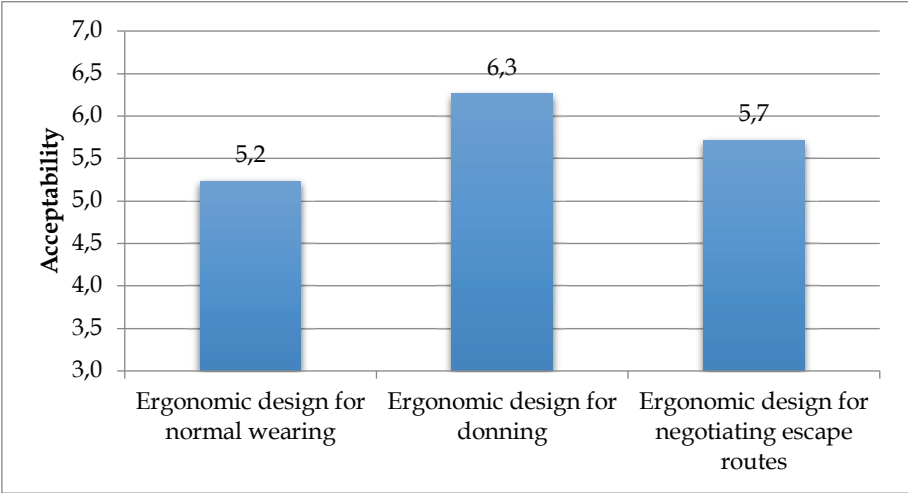


Figure 6. Ratings of the ergonomic design of SCSRs.

Table 2. Ratings of the ergonomic design of SCSRs

	Category	Average
Ergonomic design for normal wearing	a) Shape of escape apparatus (shaped to body contours, comfort)	4.7
	b) Size of escape apparatus (too bulky for routine work, or only if in confined spaces; bruising, bumping, catching)	5.1
	c) Mass of escape apparatus (are you aware of the mass of the escape apparatus, and if so how would you rate it?)	4.0
	d) Wearing arrangement - belt and suspension to belt (comfort in negating the effect of mass?)	5.6
	e) Daily affixing of escape apparatus to the body (cumbersome?)	5.0
	f) Prevention of accidental opening of escape apparatus	7.0
Ergonomic design for donning	a) Ease of manoeuvring escape apparatus into donning position	7.1
	b) Ease of opening the container	6.1
	c) Ease of handling essential parts: <ul style="list-style-type: none"> i. breathing tube ii. insertion of mouthpiece iii. fixing of nose clip 	6.0
	d) Ease of affixing and adjusting of ancillary webbing/equipment: <ul style="list-style-type: none"> i. head strap ii. bag strap iii. body strap 	6.0
Ergonomic design for negotiating escape routes	a) Accommodation for different torso lengths and sizes in respect of breathing tube and ancillary webbing, etc.	5.8
	b) Comfort <ul style="list-style-type: none"> i. nose-clip ii. mouthpiece iii. physical contact of set with body - too hot? iv. breathing resistance v. breathing temperature 	4.7
		5.4
		5.7
		6.3
		6.3

In general, it was perceived that the shape and weight of the SCSRs were not suitable for normal wearing. The suitability of the belts worn by the participants appeared to influence the results, and it was evident that the SCSRs sometimes slipped around the belt when the participants navigated the test route (e.g. when crawling). The ergonomic design for donning of the SCSRs was, on average, rated as acceptable. However, some of the participants experienced difficulty in opening the protective casings of the SCSRs, and with locating and adjusting the straps. When the SCSRs were donned and in use, the lowest score was for the comfort of the nose-clips (which are to prevent breathing in of toxic gases) as these were often noted as causing pain. The breathing tubes for some of the units appeared to be too short to comfortably accommodate all of the users. Some of the participants also commented that the SCSRs were a bit loose on the body, which could relate to how the units were fitted and the straps adjusted. Some noted that their vision was obscured when the SCSRs were donned and in use. The participants commented that they experienced neck, jaw, and tooth strain when the unit with the head (rather than neck) straps was donned, as the weight of the unit was borne by the neck and jaw rather than resting on the chest. Some noted increases in breathing resistance and air temperature when using the SCSRs, and some experienced headaches. It was possible that the units would heat up further with longer durations of use and potentially burn the chin or chest.

CONCLUSION AND RECOMMENDATIONS

The ergonomic design of SCSR devices for use by women in the SAMI was assessed. It was evident that women in the SAMI experienced pain and discomfort while wearing an SCSR on the belt during their daily work, particularly in the hips, lower back and abdomen. Most considered the SCSRs to be too heavy, and indicated that they disrupted their work. Results of the anthropometric assessment indicated that data used in the design of SCSRs might not be appropriate for women in the SAMI. Findings from the practical ergonomics assessment showed that the lowest strain was experienced when no SCSR was worn, higher strain was experienced when the SCSRs were worn on the belt, and highest strain was experienced when the SCSRs were donned and in use. The study findings indicated the need for

improved ergonomic design of SCSRs for use by women in the SAMI.

Recommendations to improve the ergonomic design of SCSRs for use by women in the SAMI were compiled with input from stakeholders and subject matter experts. As many of the factors highlighted appeared to be general, rather than specific to females, recommendations to improve the ergonomics of SCSRs for women in mining might also be expected to apply to male mine workers. Recommended interventions to improve the design and fit of SCSRs include:

- Make SCSRs lighter and smaller, as far as practically possible;
- Shape SCSRs to the contours of the body;
- Consider changes to the casing material of SCSRs;
- Ensure ease of locating parts of the SCSR when donning;
- Avoid the use of head-mounted units in future developments;
- Ensure adequate length of breathing tubes;
- Ensure adequate adjustability of neck and body straps;
- Ensure optimal design of SCSR goggles; and
- Consider changes to the wearing arrangement of SCSRs.

Related recommendations that were indicated to have high priority were:

- Ensure the provision of specific belts recommended by the respective OEMs; and
- Implement experiential and expectation training for the donning and use of SCSRs.

Further recommended research included:

- A comparative ergonomics study of males in the SAMI;
- The assessment of proposed interventions and developments; and
- Reassessment of the escape strategies of mines for female mine workers.

Appropriate implementation of the recommendations would assist with the development of interventions to improve health, safety and productivity in the mining industry.

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Jodi Pelders (Hodgskiss) is a researcher in the CSIR's mining cluster. She has been involved in researching the southern African mining industry in health and safety-related fields, including ergonomics, physiological strain, incident analysis, fatigue management, safety culture, workplace stress, and the socioeconomic and living conditions of mine workers. Jodi studied at Rhodes University where she obtained an MSc in Ergonomics. She is currently pursuing a PhD at the School of Public Health at the University of the Witwatersrand, where her research focuses on socio-demographic contributors to fatigue of mine workers in South Africa.

