Michaelson *et al. Fashion and Textiles (2024) 11:23*
https://doi.org/10.1186/s40691-024-00389-5

Fashion and Textiles

RESEARCH

Open Access

Functional performance of a novel compression top for female throwing athletes

Dawn Michaelson[1*], Sarah Gascon[2] and Karla P. Teel[1]

*Correspondence:
dawnmichaelson@gmail.com

[1] Department of Consumer and Design Sciences, Auburn University, Auburn, AL, USA
[2] School of Kinesiology, Auburn University, Auburn, AL, USA

Abstract

This study forged an interdisciplinary design partnership between an apparel designer, biomechanical kinesiologist, and a professional female athlete to design and test a novel new upper body performance garment for improved fit, mobility, comfort, donning/doffing and throwing performance in female professional athletes. Researchers collaborated to address garment functionality and performance during the multiphase prototyping design process. The final designed performance top was tested against a control for satisfaction differences with fit, mobility, comfort, donning, and doffing, along with throwing performance utilizing a mixed methods questionnaire and motion capture equipment. Open-ended questions were analyzed with content analysis, while quantitative measures utilized ANOVA and independent t-tests. Results indicated the designed performance top had higher fit satisfaction and more optimal positioning during the overhead throw when compared to the control garment, with no difference in comfort or mobility, and the designed top had lower donning and doffing satisfaction. The designed performance top illustrates the need for further research in increasing satisfaction in donning and doffing with bust/bra satisfaction in performance garments and future research to better understand the psychological sensory cues in posture cueing garments.

Keywords: Interdisciplinary design, Female athlete, Performance garment, Posture cueing, Throwing

Introduction

Overhead throwing is an action used in a myriad of female ball-throwing sports, such as handball, basketball, softball, football, and cricket. The overhead throw requires sequential movements of segments throughout the body's kinetic chain to efficiently deliver a ball to a specified target. In dynamic overhead movement, the scapula must exhibit adequate stability and mobility for efficient movement. Any breakdown in the kinetic chain can leave the athlete susceptible to injury (Bencke et al., 2018; Chu et al., 2016). More recently, research has shown the benefits of utilizing specific performance garments targeting scapular repositioning and improvement in mobility during dynamic tasks (Brophy-Williams et al., 2015; Cole et al., 2013; Gascon et al., 2018a, 2018b). Yet research has shown these garments do not always enhance the athlete's performance or satisfy garment needs (Feather et al., 1996; Michaelson et al., 2020). Performance garment functionality has been an ongoing problem for many female athletes and over the years caused discomfort, decreased mobility, limited range of motion, and performance issues (Bye & Hakala, 2005; Feather et al., 1996; Michaelson et al., 2018a, 2018b, 2020). Female athletes face many fit problems in upper body garments due to their muscular physiques and various bust sizes, as most athletic wear is made for the average female physique (Brown et al., 2014; Michaelson et al., 2020). Additionally, even athletic wear for the average female has reported fit problems (McCann, 2016; Michaelson et al., 2018a, 2018b; Zhang et al., 2019). This causes problems with performance as athletes may become distracted by their garments while playing (Michaelson et al., 2020).

Some performance garments are designed as compression garments (Cipriani et al., 2014; Michael et al., 2014; Song et al., 2015; Wallace et al., 2006). Upper body garments, typically a compression top worn over a sports bra, is used by athletes to aid them in proper body positioning during practices and competitions (Michaelson et al., 2020). Yet, research has shown that not all compression garments biomechanically cue an athlete to maintain proper posture, scapular repositioning, or alignment (Gascon et al., 2018a, 2018b; Song et al., 2015). Repetitive athletic movements and deviation from proper scapular positioning and mobility can adversely affect athletic performance (Gascon et al., 2018b; Song et al., 2015; Zappala et al., 2017). To assist an athlete in optimal scapular positioning and mobility, compression garments specifically designed to target scapular positioning have become a popular solution (Cipriani et al., 2014; Gascon et al., 2018b; MacRae et al., 2012; Michael et al., 2014; O'Sullivan et al., 2006; Wallace et al., 2006). Additionally, to rectify scapular deviations, postural taping, bracing, and compression garments have been suggested to reduce injury risk and improve performance (Cole et al., 2013; Gascon et al., 2018b; Zappala et al., 2017). However, scapular taping and bracing have been known to limit the range of motion causing altered overhead kinematics (Cole et al., 2013). Researchers have suggested that the use of compression garments may be a better alternative treatment as the effectiveness of these garments has been shown to reduce the incidence of athletic injury (Brophy-Williams et al., 2015; Gascon et al., 2018a, 2018b). Based on researcher suggestions, an interdisciplinary design partnership was forged between an apparel designer, biomechanical kinesiologist, and a professional female athlete to design and test a novel compression top for female throwing athletes.

Interdisciplinary apparel design

The interdisciplinary design aligns expertise in different disciplines or industries to collaboratively share expertise, knowledge, and skills to advance a novel idea. This approach facilitates high-order thinking by integrating discipline-specific knowledge into a single idea or project. Researchers participating in interdisciplinary research can integrate different ideas, viewpoints, and skills into a project that was only possible with the collaborative efforts of the entire interdisciplinary team. There are many benefits to conducting interdisciplinary apparel research since the shared expertise of the apparel designer, other discipline professionals, industry leaders, and even users of the apparel can share their expertise to advance the design and performance of apparel.

Performance garments come in various styles: upper body, long and short sleeve; lower body, full-body, partial length, and short length (MacRae et al., 2012; Michaelson et al., 2020). Athletes seek out performance garments to enhance their athletic performance while practicing and competing (Hayes & Venkatraman, 2016). They want task efficiency without injury from their performance garments (Bye & Hakala, 2005; Dickson & Pollack, 2000; Perry & Lee, 2017; Wheat & Dickson, 1999). Postural control and overhead throwing performance are heavily influenced by the positioning of the pelvis, trunk, scapula, and shoulder (Lewis et al., 2005; O'Sullivan et al., 2006). However, among throwing athletes, scapular positioning has been one of the most significant factors to consider when evaluating posture and optimal performance during the overhead throw (Kibler, 1998; Kibler & Sciascia, 2017).

Most performance garment studies do not report on the fabric type, and this may be due to the wearer's lack of knowledge of the fabric name or fiber content. Compression fabrics have been shown to improve an athlete's performance, aid in recovery, and are an essential factor in garment performance research (Hayes & Venkatraman, 2016; Laing & Sleivert, 2002). Past research on female athletic garments revealed that fabrics impacted mobility, performance, and caused chafing (Bye & Hakala, 2005; Feather et al., 1996; Kwok et al., 1999; Michaelson et al., 2020). Proper fabric selection can address many of these issues and increase satisfaction with using compression garments.

Researchers have reported many fit issues with female athletic apparel, but not all studies reported on the problematic body area (Brown et al., 2014; Bye & Hakala, 2005; Feather et al., 1996; Kwok et al., 1999; McCann, 2016; Michaelson et al., 2020; Tian et al., 2019; Wheat & Dickson, 1999). Some of these prior studies stated that low fit satisfaction might be due to the muscular development in female athletes (Bye & Hakala, 2005; Feather et al., 1996; Michaelson et al., 2020; Tian et al., 2019). Professional athletes have muscular development, which is more advanced than the average person due to the constant training of their sport. Athletes report dissatisfaction with garment fit as the more developed body areas do not properly fit into ready-to-wear garments. Improper fit is especially problematic when garments were initially designed as unisex or for men and used for female sports (Bye & Hakala, 2005; Laing & Sleivert, 2002; Tian et al., 2019; Wheat & Dickson, 1999). Female athletes reported problems with the neck, crotch, waist, and midriff in compression garments (Michaelson et al., 2020), shoulder, waist, chest, hip, and crotch in auto-racing suits (Tian et al., 2019), while problems with buttocks and crotch were reported in various lower body garments (Bye & Hakala, 2005; Feather et al., 1996; Michaelson et al., 2018a, 2018b). Chae and Evenson (2014) found that women had fit problems with shoulders, armholes, and waist in golf apparel.

Comfort was the highest-ranked attribute in sports garments, followed by fit for both men and women (Fowler, 1999). While not all sportswear studies rank apparel attributes, fit, comfort, mobility, donning and doffing, and performance were common attributes reported in prior research (Bye & Hakala, 2005; Chae & Evenson, 2014; Jin & Black, 2012; Michaelson et al., 2020, 2018a, 2018b). Sportswear fit is impacted by improperly sized garments and restricted mobility which affects sports performance and can be a safety issue in some sports (Bye & Hakala, 2005; Chae & Evenson, 2014; Ho & Au, 2016; Jin & Black, 2012; Kwok et al., 1999; McCann, 2016; Michaelson et al., 2020, 2018a, 2018b; Wheat & Dickson, 1999). Comfort is impacted by fabric, fit, improper sizing, and seams in the apparel (Bye & Hakala, 2005; Chae & Evenson, 2014; Feather et al., 1996; Kwok et al., 1999; Michaelson et al., 2020; Perry & Lee, 2017). Donning and doffing are impacted by fabric selection, closures, and fit (Bye & Hakala, 2005; Kwok et al., 1999; Michaelson et al., 2020, 2018a, 2018b). Seam comfort can directly impact fit when discomfort is experienced (Ho & Au, 2016).

Upper body compression garments come in various designs, some with and without shoulder straps. The biomechanical influence of compression garments with shoulder straps cues the athlete to maintain optimal posture and improve scapular alignment. Specifically, the shoulder straps target the posterior shoulder to improve scapular positioning and restore normal shoulder kinematics. Compression garments without shoulder straps are constructed in an attempt to signal or promote activation of the lumbopelvic-hip complex (LPHC) and scapular muscles for better postural alignment of an individual's shoulders, spine, and trunk (Gascon et al., 2018a, 2018b). This is achieved through a proprioceptive feedback mechanism. Proprioceptive feedback is muscle-joint input that provides information regarding a position in space and/or in relation to objects. The pressure of the posture cueing garment provides cutaneous sensory cues providing input to the central nervous system. These sensory cues will allow specific musculature to signal the body to maintain a more upright and proper posture (Gascon et al., 2018a, 2018b). These posture cueing garments are directly linked to improved athletic performance and have been shown to assist baseball pitchers and tennis athletes during the execution of sport-specific tasks (Gibbs et al., 2014; Zappala et al., 2017). However, limited data supports the kinematic influence of posture cueing garments among athletes during the overhead throw.

Based on the literature review, a novel compression top with posture-cueing was designed and then wear-tested to investigate the following research questions in this study:

- What, if any, are the garment satisfaction differences with fit, mobility, comfort, and don/doffing, between the control and novel compression top?
- Are there any kinematic differences in scapular protraction/retraction rotation, lateral/medial rotation, and anterior/posterior tilt during an overhead throw at the four throwing events of foot contact, external shoulder rotation, ball release, and internal shoulder rotation between the control and novel compression top to signify the posture cueing device is improving performance?

Prototyping design process

The novel compression top was designed collaboratively with a team consisting of an apparel designer and a biomechanical kinesiologist. This collaboration enabled the compression top to be both functional and aesthetically pleasing, while considering performance aspects for a professional female athlete. Prior apparel researchers have stated that athletes prefer both functional and aesthetics in their athletic wear (Dickson & Pollack, 2000; Feather et al., 1996; Michaelson et al., 2020; Wheat & Dickson, 1999) while kinesiology studies focus on the garments' ability to improve an athlete's performance, such as the overhead throw (Cole et al., 2013; Gascon et al., 2018b).

A professional female athlete was identified as a fit model for prototype development. The model identified participated in multiple collegiate throwing sports, was on an Olympic team, had an athletic body structure from years of athletic training, and could articulate apparel issues to the design team. A 3D body scan was obtained to obtain accurate body measurements, which the apparel designer then used to draft the initial compression top patterns. Fabric samples were ordered and chosen based on stretch, compression qualities, thermal properties, and weight. Black was chosen for uniformity, as compression fabrics had limited color options. Initially, four stretch fabrics were chosen: (a) compression tricot with MaxDri™ and MicroBlok™ finishes (70% nylon, 30% spandex, 285 gsm) for compression benefits; (b) Spandura™ with Coolmax™ finish (90% Cordura nylon, 10% spandex, 350 gsm) for stretch and wicking purposes; (c) mesh bonded compression (90% nylon, 10% spandex, 310 gsm) for contrast and compression benefits; and (d) sport lining mesh (85% nylon, 15% spandex, 85 gsm) for breathability. All study prototypes were constructed on a flatlock industrial machine and hemmed with an industrial coverstitch machine. All machines used Max-Lock® serger spun polyester thread—Tex 27 and A&E Best Stretch® textured nylon thread in the lower loopers only for seam strength, stretch, and comfort.

First prototype for garment functionality

The design team's initial prototype goal was to achieve feminine style lines and adequate comfort and mobility. The design team met weekly to discuss the design and functional capabilities needed in the initial compression top. The first prototype featured raglan short sleeves, crew neckline, 2-inch band under bust, stylized bust seams, and curved hip inserts. The super stretch compression tricot with MaxDry™ and MicroBlok™ finishes was used on the sleeves, center piece of bust, and the lower torso for compression benefit. The Spandura™ with Coolmax™ finish was used on the remaining bust pieces, back, and hip inserts for stretch and wicking. Mesh-bonded compression fabric was used for the bust band and the stylized area next to the raglan sleeve as contrast. All seams were superimposed (SSa) with a four-thread overlock (ASTM 514) stitch (ASTM International, 2011).

The fit model wore the initial prototype during a standard workout and provided feedback to the design team during a meeting. She indicated fit improvements were needed in the neck, shoulders, armhole circumference, torso length, and bust. The fit model also reported "heaviness after a workout" where the Spandura™ fabric was used. After the fit model provided her report, the design team discussed each of the concerns and mutually agreed to changes based on their personal knowledge of fabric properties, garment design, biomechanical requirements of the athlete, and athletic expertise, and then hypothesized changes to the garment. The biomechanical kinesiologist and fit model provided additional education to the apparel designer on the movement requirements for throwing and the typical problematic fit issues resulting from throwing. It was decided that the Spandura™ would be removed from subsequent prototypes as it did not provide sufficient wicking and breathability. It was replaced with the super stretch compression tricot, which provided the model with "a feeling of being cool". A built-in sports bra was also recommended to improve thermal comfort by eliminating excessive heat in the bust area. The fit model initially needed to wear a sports bra under the first prototype for bust support, which added 2 layers of additional fabric to the bust area creating thermal discomfort.

Subsequent prototypes for functionality and performance

After each subsequent prototype was developed and given to the fit model, the design team would meet weekly for continued interdisciplinary discussions. They improved the overall compression top design for better fit, comfort, and mobility. Based on these meetings and discussions, the raglan sleeves were removed, and a sleeveless style was implemented. Flatseaming (FSa) with flatlock stitching (ASTM 607) was used for seam strength and to improve comfort, especially with rubbing and chafing in all subsequent prototypes (ASTM International, 2011). Then, an integrated sports bra and posture cueing device were incorporated. The sports bra with foam cup was designed using a wicking mesh liner fabric to avoid excess heat during workouts or competitions. This was a common complaint based on the biomechanical kinesiologist's expertise and the fit model's athletic experience. The fit model reported high heat under the arms and therefore, the pattern was adjusted to include an underarm insert using the mesh liner fabric. She also suggested using wider elastic under the bust as many sports bras with one inch or narrower elastic moved while performing, which caused distraction while competing. Two-inch elastic was used to provide a more secure fit for the athlete. The design team discussed posture cueing to find a way to achieve optimal scapula positioning within the garment while not hindering throwing mobility. In sports, kinesio tape, an elastic adhesive tape, is used to secure the scapula in a criss-cross manner to provide stability. A similar criss-cross design was suggested by Johnson (2011) for a posture bra, so the design team adapted this design for the posture cueing device within the performance top. A wide 2-inch braided elastic was used for the posture cueing device. The device was placed between the sports bra and outer garment top except for an opening which allowed the wearer to tighten or loosen to the device. The device was attached to the top of the bra cups, crisscrossed between the scapula, then attached to the side of the bra cup or the side closure. An infrared camera was used during fitting sessions to reveal if thermal comfort was being achieved with the subsequent changes before a wear trial. All these changes were incorporated into a prototype worn by the fit model and two other female athletes for at least one workout or practice session. Fit model feedback included feeling "powerful" and "invincible" along with strong satisfaction with apparel fit, mobility, and comfort. As there were no further design issues to be addressed, the design team made the decision to use this design for wear trial testing.

Final prototype for wear trial testing

After months of garment redesign and fit testing, the interdisciplinary design team collaboratively agreed to a final prototype for wear testing. The final compression top comprised of 15 outer parts. Based on infrared heat mapping, super stretch compression was used for the center front upper torso, back, and lower torso pieces for wicking. Bonded compression with macro mesh was used in three upper torso pieces from the shoulder through the bust to help control bust movement and a 2-inch strip under the bust. Sports bra fit adjustments made donning and doffing difficult, so a wide hook and eye bra closure were added on the side. A front bra closure was not ideal based on fit model concerns of a possible injury if they fell on their chest. A back bra closure would also be problematic due to the tightness of the compression top and length of the top. Mesh lining, fabric D, was used at the side insert, center front insert, and for the sports bra liner. Super stretch compression, fabric A, was used for the main body portions. Bonded compression with macro mesh, fabric C, was used under the bust, curved along the shoulders, and a portion of the center front pieces for contrast. Fabric placements within the final prototype, posture cueing device, sports bra closure, and stitches can be seen in Fig. 1. Wear testing tops were graded into 5 sizes: extra small to extra-large and based on over 30 body scans from potential female throwing athlete participants. The researchers used the control top sizing chart to group the body-scanned participants into similar sizing ranges based on bust and waist measurements.

Methods

Questionnaire development

A mixed-method questionnaire was developed using established measures from prior published garment studies and three open-ended questions (Barker, 2002; Cox & Cox, 2002; Huck et al., 1997; LaBat & DeLong, 1990; Wheat & Dickson, 1999). All scales were modified to a 7-point Likert-type satisfaction scale (1 = very dissatisfied to 7 = very satisfied). LaBat and DeLong's (1990) Fit Satisfaction Scale was modified for upper body areas by adding back length'. All semantic scales in the questionnaire start at one for the negative side, such as dislike, then increase to seven for the positive side, such as like. The three researchers developed open-ended questions for additional clarification on participant's perceptions of the novel top: (1) list any problems you experienced in the compression garment; (2) provide any feedback about the compression garment style,

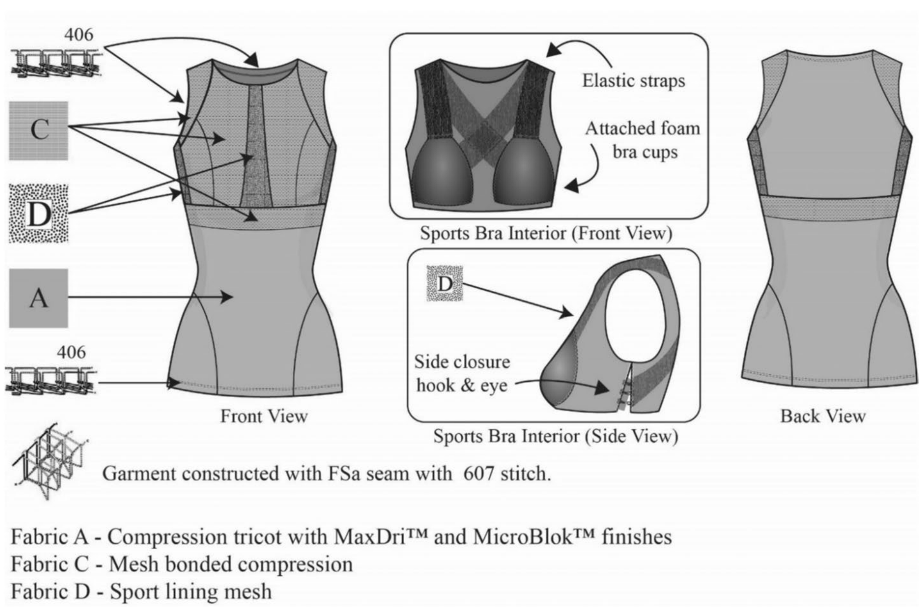

Fig. 1 Final prototype design, fabric, stitches, and seams

colors, construction, etc.; and (3) provide any feedback about the built-in bra or posture cueing features.

Sample and data collection

After obtaining institutional review board approval (Auburn University, IRB 16-079 EP 605) that included ethical protection of human participants in this research, the researchers commenced a two-part study consisting of kinematic data on the posture cueing device effectiveness during a 60-foot overhead throw and a mixed-methods questionnaire on garment satisfaction for both the control and novel top. Twenty female throwing athletes from a southeastern university participated and met the following criteria: (a) female athlete (19–30 years); (b) actively participates in a throwing sport; (c) medically cleared to participate in overhead throwing activities; and (d) have not had any injuries within the last six months. The "control" compression top used in this study was purchased at a local athleticwear store. One specific brand and style were chosen and then purchased in 5 sizes: extra-small to extra-large. The control top was similar to the novel top based on neckline style, no sleeves, and top length (see Fig. 2). Participants wore the control top and their own sports bra during the wear trial. This section lists the number of subjects and their gender; there were 20 females between the ages of 19 and 30.If needed, the mean age was 20 years. The participants were not requested to provide height and weight for thisstudy.

Study performance tops

The novel compression top was graded and constructed in the five sizes. All of the compression tops, control and novel, were given to the participants based on their bust and waist measurements. Other clothing worn by the participants during the study, such as shorts, pants, undergarments, etc., were owned by the participant, were typical practice garments, and were not controlled for in the study.

All data were conducted in a controlled laboratory setting. Testing was conducted on two separate days, 24–72 h apart, in the following manner: (1) the control top and sports bra; and (2) the designed top with a built-in sports bra. All participants had tracking system sensors attached to their upper bodies synchronized with The MotionMonitor (Innovative Sports Training, Chicago, IL) to collect kinematic data. Once all tracking system sensors were secured and digitization completed, participants were given verbal instructions to perform their own non-standardized, throwing warm-up to avoid the risk of injury. Afterward, the participant executed five-game effort throws to a catcher 60 feet away for both garment conditions on separate days. After collecting kinematic data, the participants completed the garment satisfaction questionnaire for the control and novel compression top.

Data analysis

All data analysis for this study was conducted using SPSS Statistics, Version 26, statistical software. Open-ended question responses were entered into an Excel spreadsheet for coding using a content analysis approach. Two separate coders evaluated each response and assigned it a theme(s). Once all data were coded, it was imported into SPSS Statistics

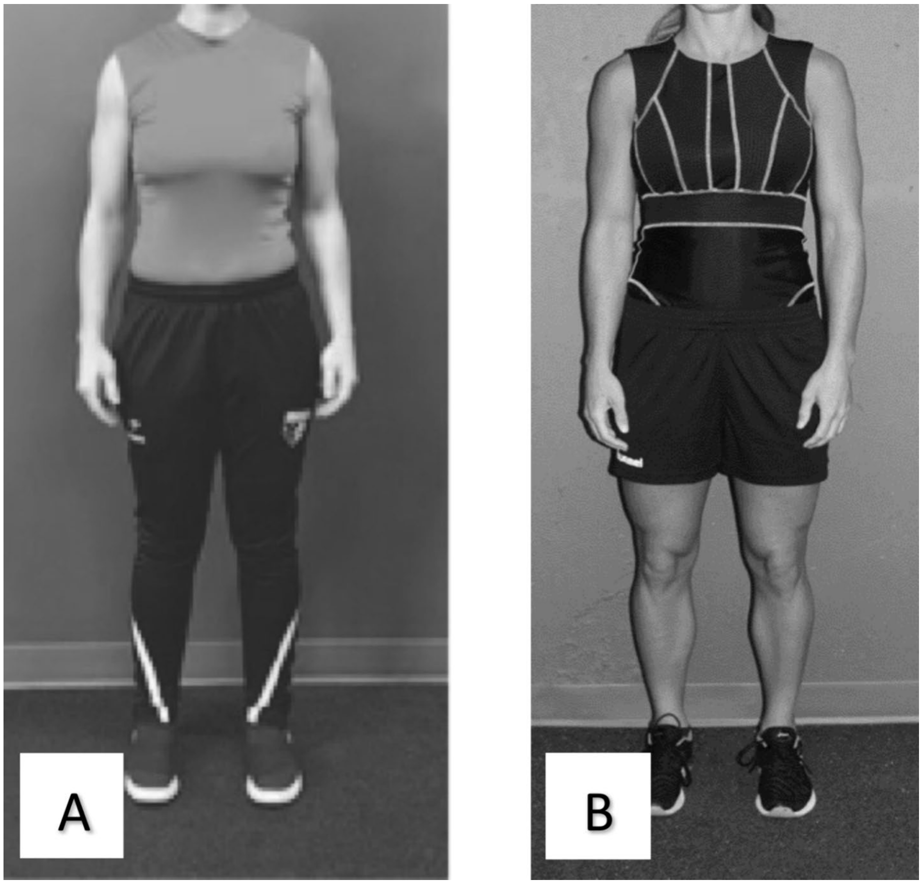

Fig. 2 **A** Control compression top. **B** Novel compression top

for intercoder reliability. Not all participants responded to each open-ended question resulting in a total of 45 responses and intercoder reliability was confirmed ($\kappa \le 0.78$). Quantitative data was entered into SPSS Software for analysis. Scale reliability was confirmed for all measures ($\alpha \le 0.78$).

Results

The researchers investigated whether garment differences existed between the control and novel compression top for fit, mobility, comfort, don/doffing, usefulness, likeability, and performance benefits from the posture cueing device. Researchers collected kinematic data of an overhead throw from all twenty female throwing athletes, followed by a mixed method questionnaire for both garment conditions. Participants were female athletes that were actively playing a throwing sport (70% softball, 30% multiple throwing sports), their ages ranged from 19 to 27 years (age 21.85 ± 2.43), the majority were Caucasian (90%), and most were at a junior (45%) or graduate (30%) academic level. Table 1 features the descriptive and AVOVA statistics for all the variables. When sphericity was violated in some of the ANOVA statistics, Greenhouse–Geisser corrected results were reported in these instances. Table 2 represents the results of the qualitative data obtained from the three open-ended questions.

Garment satisfaction differences

Fit

A repeated measures analysis of variance (ANOVA) was conducted to compare the effect of fit area satisfaction and garment conditions. There was a significant effect on fit area satisfaction by garment condition, $F(4.946, 187.961) = 4.030$, $p = 0.002$, $\eta^2 = 0.096$. Independent samples *t*-test were then conducted between garment conditions. There was a significant difference in bust satisfaction by garment condition, $t(38) = 2.724$, $p = 0.004$, and shoulder blade satisfaction by garment condition, $t(38) = 0.914$, $p = 0.047$. Qualitative data noted that the novel compression top fit satisfaction varied among the participants, with some liking the fit to others not liking the fit due to it being too tight. These results suggest that fit area satisfaction does influence garment condition. The novel garment fit satisfaction increased in all fit areas compared to the control garment except for bust and shoulder blade areas which decreased, see Table 1. No qualitative responses explained the shoulder blade fit problems, while the bust fit problems appear to have resulted from the built-in bra and bust support. The bust fit was only slightly satisfying for the novel compression top (M = 5.00) and not all participants liked the built-in bra. Participants stated the built-in bra "has to go", "highly uncomfortable", and "cups were difficult to fit".

Mobility

A repeated measures ANOVA was conducted to compare the effect of mobility satisfaction and garment conditions. There was no significant effect on mobility satisfaction by garment conditions, $F(2.798, 95.127) = 0.814$, $p = 0.482$. While there was no significant difference in means, it should be noted that participants rated "like" higher in the control garment (M = 5.89) than the novel garment (M = 5.28). Additionally, participants rated tightness higher in the novel top (M = 5.22) than the control top (M = 4.67). These results indicate that mobility was similar between the compression tops. The novel compression top was made of compression fabric and designed to be form-fitting, so the tightness rating was foreseeable.

Comfort

A repeated measures ANOVA was conducted to compare the effect of comfort satisfaction and garment conditions. There was no significant effect on comfort satisfaction by garment conditions, $F(5.719, 211.609) = 1.697$, $p = 0.127$. Independent samples *t*-test found a significant difference for clingy in the novel (M = 5.70) versus control (M = 5.15) top; $t(38) = -1.193$, $p = 0.041$. Clingy can be associated with compression fabric and a tighter fit (Michaelson et al., 2020). Qualitative data results found some comfort satisfaction comments were related to fabric properties, such as "helps to keep me cool" and "felt nice when I had it on." Comfort dissatisfaction mainly was related to the bust and bra comfort, with comments such as "bust was tight" and "bra was uncomfortable".

Donning and doffing

Independent samples *t*-test found a significant difference for donning [$t(38) = 6.340$, p = 0.000] and doffing [$t(38) = 5.984$, p = 0.000] between the garment conditions. When

Table 1 Quantitative variables for novel compression top

Variable	Novel top		Control top		ANOVA			
	M	SD	*M*	SD	Effect	*F* ratio	*df*	Sig
Fit areas								
Neck	6.10	1.17	5.85	1.14	**V**	**2.63**	**10**	**0.00**
Shoulder	6.15	1.04	5.55	1.76	G	0.10	1	0.75
Armhole	5.95	1.23	5.75	1.48	**V x G**	**4.03**	**4.95**	**0.01**
Upper Arm	6.30	1.17	5.95	1.36				
Lower Arm	6.40	1.27	6.00	1.38				
Bust	5.00	1.84	6.20	0.70				
Shoulder Blade	5.60	1.57	6.00	1.17				
Midriff	5.85	1.27	5.60	1.50				
Waist	5.85	1.39	5.80	1.11				
Abdomen	6.05	1.00	5.70	0.94				
Back Length	6.40	0.75	6.10	1.07				
Mobility								
Comfortable–Uncomfortable	6.11	1.32	6.39	0.78	**V**	**8.95**	**8**	**0.00**
Acceptable–Unacceptable	6.50	0.92	6.50	0.71	G	0.27	1	0.61
Flexible–Stiff	6.44	0.92	6.56	0.51	V **x** G	0.82	2.80	0.48
Arm movement–Arm restricted	6.67	0.59	6.56	0.86				
Ease–Hard to move in	6.22	1.22	6.56	0.71				
Satisfactory–Unsatisfactory	5.61	1.58	5.72	1.67				
Torso movement–Torso restricted	6.06	1.35	6.44	0.86				
Like–Dislike	5.28	2.22	5.89	1.78				
Tight–Loose	5.22	1.83	4.67	1.72				
Comfort								
Snug	6.00	1.05	5.55	1.05	**V**	**3.84**	**10**	**0.02**
Sticky	5.74	1.49	5.35	1.76	G	0.23	1	0.64
Heavy	5.42	1.54	5.50	1.67	V **x** G	1.70	10	0.13
Nonabsorbent	5.47	1.74	5.15	2.06				
Stiff	5.53	1.84	5.55	1.64				
Clammy	5.58	1.74	4.95	1.85				
Damp	5.68	1.70	5.05	1.85				
Non-stretchy	5.00	1.83	5.60	1.60				
Clingy	5.74	1.20	2.15	1.69				
Scratchy	5.74	1.63	5.85	1.57				
Prickly	6.05	1.47	5.95	1.57				
Don/Doff								
Easy–hard to put on	3.70	2.11	6.75	0.44				
Easy–hard to take off	4.00	2.05	6.80	0.41				
PCK—Scapular protraction/retraction (degrees ±)								
Foot contact	0.51	21.0	0.12	15.5	G	2.17	1.00	0.16
Shoulder external rotation	**− 0.92**	**15.9**	**7.40**	**10.4**	E	38.7	1.51	0.01
Ball release	11.2	14.4	16.0	10.7	**G x E**	**5.23**	**1.68**	**0.02**
Shoulder internal rotation	23.5	16.1	27.2	13.7				
PCK—Scapular lateral/medial rotation (degrees ±)								
Foot contact	− 29.6	19.3	− 28.4	14.9	**G**	**5.34**	**1.00**	**0.03**
Shoulder external rotation	− 27.1	16.7	− 23.0	13.7	E	26.9	1.69	0.01
Ball release	**− 19.1**	**15.3**	**− 10.5**	**11.0**	**G x E**	**12.2**	**38.4**	**0.01**
Shoulder internal rotation	**− 15.9**	**14.1**	**− 6.73**	**8.80**				

Table 1 (continued)

Variable	Novel top		Control top		ANOVA			
	M	SD	*M*	SD	Effect	*F* ratio	*df*	Sig
PCK—Scapular anterior/posterior tilt (degrees ±)								
Foot contact	− 2.79	14.2	− 0.31	10.4	G	2.94	1.00	0.10
Shoulder external rotation	12.5	10.0	7.81	11.6	E	14.2	1.92	0.01
Ball release	**5.44**	**9.25**	**0.06**	**9.01**	**G x E**	**3.95**	**1.93**	**0.03**
Shoulder internal rotation	**3.42**	**11.1**	**− 2.36**	**8.60**				

F ratio is a statistical test in the analysis of variance (ANOVA) that measures the ratio of variability between groups to the variability within groups

N = 20. ANOVA, analysis of variance; V, variable, G, garment condition, E, event, PCK, posture cueing kinematics

Bold denotes significance

donning and doffing the garments, the control top ($M_{don} = 3.70$, $M_{doff} = 4.00$) was easier than the novel top ($M_{don} = 6.75$, $M_{doff} = 6.80$) for both tasks. Participants found that the novel top was overall difficult to put on and off, difficult due to body shape, along with bra clasp usage. Prior research found similar results with female compression garments regarding donning and doffing satisfaction (Michaelson et al., 2020).

Posture cueing performance differences

All kinematic variables for the overhead throw variables were analyzed using repeated measures ANOVA in both garment conditions. Results indicate a significant effect of garment for scapular medial/lateral rotation [$F(1.00,1.69) = 5.34$, $p = 0.03$], and a significant garment by event interactions for protraction/retraction [$F(1.00,1.89) = 5.23$, $p = 0.02$], lateral/medial rotation [$F(1.00,38.4) = 12.20$, $p = 0.01$], and anterior/posterior tilt [$F(1.00,1.93) = 3.95$, $p = 0.03$]. Post-hoc results revealed significance in protraction/retraction at shoulder external rotation, lateral/medial rotation, and anterior/posterior tilt at ball release and internal shoulder rotation ($p < 0.05$). Results revealed the novel compression top showed an increase in scapular retraction during maximum shoulder external rotation ($p < 0.02$), an increase in lateral rotation at ball release ($p < 0.01$) and maximum shoulder internal rotation ($p < 0.01$), and an increase in posterior tilt at ball release ($p < 0.02$) and maximum shoulder internal rotation ($p < 0.04$) compared to the control top. It should be noted that not all participants had sensory cues indicating the posture cueing in the novel top, see Table 2. The current study allowed for a more optimal scapular position during the overhead throw. However, the novel top illustrates the need for further biomechanical research between compression garments during dynamic movements.

Discussion

This study investigated the garment satisfaction differences between a control and a novel interdisciplinary-designed compression top, along with any kinematic differences during an overhead throw while wearing each garment. Fit satisfaction indicated problems with the bust and shoulder blades. Brown et al. (2014) found similar bra fit issues with 75% of female marathon runners reporting a bra fit problem. Bra fit can change with a female's age and bust size therefore bra fit is an area of dissatisfaction for many

Table 2 Qualitative feedback on novel compression top

Question	Theme	*f*	Comment examples
Problems experienced	Don/doff	11	"extremely hard to get on/off", "difficult to fasten", "little tricky going on", and "little harder to put on with my body type"
	Bra/bust	6	"bust was small/tight", "breast cups were difficult to fit well", and "built-in bra was highly uncomfortable"
	Fit	5	"band was a little tight", "breast cups were difficult to fit", "little tight"
	Comfort	5	"bust was small/tight", "built-in bra was highly uncomfortable", and "tight in the chest"
	Style	1	"really wish garment had sleeves"
	Fabric	1	"take off compression"
Style, colors, construction, etc	Style	7	obviously made for women which I like", "did not like the look", "like the cut", "neck unflattering", "razorback or v-neck options", and "style was great"
	Color	5	"prefer neutral colors but would also wear other colors", "liked color", "black color is practical", and "black is always flattering"
	Comfort	4	"under breast area non stretchable", "felt nice when I had it on", "pretty tight", and "helps to keep me cool"
	Fit	3	"liked it" and "did not like the fit"
	Superhero identity	3	"feel like Katniss Everdeen", "looked like Angelina Jolie in Tomb Raider", and "feel like Wonder Women"
	Don/doff	2	"it was too difficult to put on" and "bra without clasp would be easier"
	Reference to another garment	2	"similar to a snug tank" and "better than the first one (control garment)"
Posture cueing and built-in bra features	Bra	9	"built-in bra has to go", "built-in bra was nice", "built-in bra could be secured better", "bra moved around less while moving which gave less distraction when performing", and "love the idea of built-in sports bra"
	Comfort	7	"band a little tight", "anterior side felt very comfortable and secure", "bra was uncomfortable", "uncomfortable", "felt comfortable while wearing", "not super uncomfortable", and "too loose in breast area"
	Fit	5	"really like the fit", "did not fit", "fit very well", and "too form fitting around waistband"
	Posture cueing	3	"wish I could feel the pull", and "felt my shoulders more retracted than normal"
	Don/doff	2	"difficult to put on and take off" and "needs to be easier to put on"
	Bust support	2	"did not provide support" and "supportive"
	Sizing	1	"chest sizes instead of small, medium, and large"

Table 2 (continued)

F ratio is a statistical test in the analysis of variance (ANOVA) that measures the ratio of variability between groups to the variability within groups

females. Similarly, bust size impacts fit especially when the cup size increases. This study found that fit dissatisfaction centered on the built-in bra and bust support. The built-in bra impacted not only fit but mobility, comfort, and don/doffing of the novel top. While having a built-in bra can aid in thermal comfort, it may come at the sacrifice of fit, mobility, bra discomfort, and don/doffing difficulties. Shoulder blade dissatisfaction was not fully understood in this study. Still, it should be noted that improper width of shoulders in performance apparel has been known to cause dissatisfaction in prior studies (Tian et al., 2019) and should be explored in future studies. The tightness of the novel compression top may lead to discomfort for those who do not prefer compressive garments as some participants stated it felt too tight. The fabric choice in the novel top was found to be comfortable with a cooling effect which may be due to the wicking and breathability fabric properties. Similarly, female basketball and golf players preferred garments for breathability and comfort to avoid chafing, cling, and excess moisture on their body (Chae & Evenson, 2014; Feather et al., 1996). Additionally, Zhang et al. (2019) reported that sports bras should not be overly tight and must provide breathability for comfort. Regarding the breathability, the novel compression top fabric while compressive was comfortable for participants. The athletic body shape may also pose additional fit and don/doffing issues (Bye & Hakala, 2005; Feather et al., 1996; Michaelson et al., 2020; Tian et al., 2019). Even though the novel compression top was specifically designed for an athletic female athlete various body shapes still existing and designing garments to fit all shapes is not possible. Overall, the novel top provided performance enhancement with the posture cueing device and has good overall garment satisfaction. This study adds to the limited body of research for female athletic garments, built-in bra garments, female performance enhancing garments, and the benefits of interdisciplinary design research.

Interdisciplinary design reflection after prototyping

The design team reflected on working collaboratively on apparel development at the end of the prototyping process. The design team better understood both disciplines and the work done in each industry. Many of the developments to the prototype would not have been considered without the other team member's knowledge and the feedback of the fit model. The biomechanical kinesiologist did not know textiles, patternmaking, or garment manufacturing so they did not realize the impact it had on the garment's overall functionality. The apparel designer did not have expertise in the biomechanics of throwing, musculoskeletal system, athletic performance, or injury/exercise recovery techniques used with athletes. By meeting regularly to discuss the fit model's feedback, the design team could work together to achieve a final prototype that both members hoped would be advantageous for a female athlete.

Conclusions

The current study included a novel compression top explicitly constructed for female athletes, which was found to provide increased fit satisfaction and allowed for more optimal scapular positioning during the overhead throw. Both study garments had satisfactory comfort and mobility satisfaction, with no significant differences between the garment conditions. The built-in bra had mixed results, so it is advised that manufacturers provide options for consumers to choose a top with a built-in bra or a top without one. The novel compression top illustrated the need for further research in increasing satisfaction in donning and doffing, closure location, and bust/bra fit and comfort satisfaction in compression garments. Compression fabrics for garments should have excellent breathability and wicking features to help with comfort and mobility satisfaction. Future garment research is needed in several areas including female athletic body shapes, built-in bras, bust comfort in compression garments, and better understanding of the sensory cues in posture cueing devices. This studies interdisciplinary design approach gave insights into biomechanical functions used in sports, apparel fit problems experienced by female athletes, and their corresponding psychological impacts, which aided all researchers in this study. Athletic apparel designers can benefit from an interdisciplinary approach to further apparel design functionality and performance research.

Acknowledgements

This research was conducted under the approval and supervision of the Auburn University Institutional Review Board (IRB Approval No. 16-079 EP 605) regarding ethical issues, including consent to participants.

Author contribution

D.M, S.G contributed equally to the study, prototype design process, data collection, and data analysis. K.P.T provided guidance for the study as a supervisor. D.M was solely responsible for manuscript development while second and third author reviewed the manuscript prior to submission for editorial revisions.

Funding

All funding was provided by the author(s).

Availability of data and materials

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

Declarations

Competing interests

The author(s) declare(s) that they have no competing interests.

Received: 18 February 2022 Accepted: 7 May 2024
Published online: 28 June 2024

References

ASTM International. (2011). *ASTM D 6193–11, Standard practice for stitches and seams* (Vol. 6193). West Conshohocken: ASTM International.

Barker, R. L. (2002). From fabric hand to thermal comfort: The evolving role of objective measures in explaining human comfort response to textiles. *International Journal of Clothing Science and Technology, 13*(3/4), 181–200.

Bencke, J., van den Tillaar, R., Møller, M., & Wagner, H. (2018). Throwing biomechanics: aspects of throwing performance and shoulder injury risk. In L. Laver, P. Landreau, R. Seil, & N. Popovic (Eds.), *Handball sports medicine: Basic science, injury management and return to sport* (pp. 64–74). Springer.

Brophy-Williams, N., Driller, M. W., Shing, C. M., Fell, J. W., & Halson, S. L. (2015). Confounding compression: The effects of posture, sizing and garment type on measured interface pressure in sports compression clothing. *Journal of Sports Sciences, 33*(13), 1402–1410. https://doi.org/10.1080/02640414.2014.990489

Brown, N., White, J., Brasher, A., & Scurr, J. (2014). An investigation into breast support and sports bra use in female runners of the 2012 London Marathon. *Journal of Sports Sciences, 32*(9), 801–809. https://doi.org/10.1080/02640414.2013.844348

Bye, E., & Hakala, L. (2005). Sailing apparel for women: A design development case study. *Clothing and Textiles Research Journal, 23*(1), 45–55.

Chae, M., & Evenson, S. (2014). Prototype development of golf wear for mature women. *International Journal of Fashion Design, Technology and Education, 7*(1), 2–9. https://doi.org/10.1080/17543266.2013.837966

Chu, S. K., Jayabalan, P., Kibler, W. B., & Press, J. (2016). The kinetic chain revisited: New concepts on throwing mechanics and injury. *Physical Medicine and Rehabilitation, 8*(3 Suppl), S69-77. https://doi.org/10.1016/j.pmrj.2015.11.015

Cipriani, D. J., Yu, T. S., & Lyssanova, O. (2014). Perceived influence of a compression, posture-cueing shirt on cyclists' ride experience and post-ride recovery. *Journal of Chiropractic Medicine, 13*(1), 21–27. https://doi.org/10.1016/j.jcm.2014.01.007

Cole, A. K., McGrath, M. L., Harrington, S. E., Padua, D. A., Rucinski, T. J., & Prentice, W. E. (2013). Scapular bracing and alteration of posture and muscle activity in overhead athletes with poor posture. *Journal of Athletic Training, 48*(1), 12–24. https://doi.org/10.4085/1062-6050-48.1.13

Cox, D., & Cox, A. D. (2002). Beyond first impressions: The effects of repeated exposure on consumer liking of visually complex and simple product designs. *Journal of the Academy of Marketing Science, 30*(2), 119–130.

Dickson, M. A., & Pollack, A. (2000). Clothing and identity among female in-line skaters. *Clothing and Textiles Research Journal, 18*(2), 65–72.

Feather, B. L., Ford, S., & Herr, D. G. (1996). Female collegiate basketball players' perceptions about their bodies, garment fit and uniform design preferences. *Clothing and Textiles Research Journal, 14*(1), 22–29.

Fowler, D. (1999). The attributes sought in sports apparel: A rating. *Journal of Marketing Theory and Practice, 7*(4), 81–88.

Gascon, S. S., Gilmer, G. G., Hanks, M. M., Washington, J. K., & Oliver, G. D. (2018a). Biomechanical influences of a postural compression garment on scapular positioning. *International Journal of Sport Physical Therapy, 13*(4), 700–706.

Gascon, S. S., Washington, J. K., Gilmer, G. G., & Oliver, G. D. (2018b). Influence of posture-cueing compression garment on overhead throwing kinematics. *Journal of Clinical Diagnosis and Treament, 1*(1), 1–7.

Gibbs, S., Weaver, F., House, T., & Vangsness, T. (2014). The effects of a posture shirt on throwing velocity, throwing accuracy and blood flow in professional baseball pitchers: A pilot study. *Department of Orthopaedic Surgery, Keck School of Medicine., 14*, 27783705.

Hayes, S. G., & Venkatraman, P. (2016). *Materials and technology for sportswear and performance apparel*. CRC Press.

Ho, C., & Au, Y. (2016). Development of functional racing singlet for professional rowers. *International Journal of Fashion Design, Technology and Education, 10*(2), 1–9. https://doi.org/10.1080/17543266.2016.1221144

Huck, J., Maganga, O., & Kim, J. (1997). Protective overalls: Evaluation of garment design and fit. *International Journal of Clothing Science and Technology, 9*(1), 45–61.

Jin, H., & Black, C. (2012). Assessing functional and aesthetics clothing needs of young male tennis players. *International Journal of Fashion Design, Technology and Education, 5*(2), 145–150.

Johnson, B. (2011). *The bra makers manual* (Vol. 2). Turtle Press.

Kibler, W. B. (1998). The role of the scapula in athletic shoulder function [review]. *American Journal of Sports Medicine., 26*(2), 325–337.

Kibler, W. B., & Sciascia, A. D. (2017). *Disorders of the scapula and their role in shoulder injury: A clinical guide to evaluation and management*. Springer.

Kwok, Y. L., Kong, P. Y., & Fan, J. (1999). Development of swimwear for diving. *Research Journal of Textiles and Apparel, 3*(2), 27–33.

LaBat, K. L., & DeLong, M. R. (1990). Body cathexis and satisfaction with fit of apparel. *Clothing and Textiles Research Journal, 8*(2), 43–48.

Laing, R. M., & Sleivert, G. G. (2002). Clothing, textiles, and human performance. *Textile Progress, 32*(2), 1–12. https://doi.org/10.1080/00405160208688955

Lewis, J. S., Wright, C., & Green, A. (2005). Subacromial impingement syndrome: The effect of changing posture on shoulder range of movement. *Journal of Orthopaedic & Sports Physical Therapy, 35*(2), 72–87.

MacRae, B. A., Laing, R. M., Niven, B. E., & Cotter, J. D. (2012). Pressure and coverage effects of sporting compression garments on cardiovascular function, thermoregulatory function, and exercise performance. *European Journal of Applied Physiology, 112*(5), 1783–1795. https://doi.org/10.1007/s00421-011-2146-2

McCann, J. (2016). Sportswear design for the active ageing. *Fashion Practice: THe Journal of Design, Creative Process & the Fashion, 8*(2), 234–256. https://doi.org/10.1080/17569370.2016.1215118

McLoughlin, J., & Hayes, S. (2015). Joining techniques for sportswear. In R. Shishoo (Ed.), *Textiles for sportwear* (pp. 119–149). Woodhead Publishing Limited.

Michael, J. S., Dogramaci, S. N., Steel, K. A., & Graham, K. S. (2014). What is the effect of compression garments on a balance task in female athletes? *Gait and Posture, 39*(2), 804–809. https://doi.org/10.1016/j.gaitpost.2013.11.001

Michaelson, D., Gascon, S., & Teel, K. P. (2020). Investigating female athlete's compression garment needs and satisfaction levels. *International Journal of Fashion Design, Technology and Education, 13*(3), 247–255. https://doi.org/10.1080/17543266.2020.1782481

Michaelson, D., Kim, D.-E., & Ha, Y. (2018a). Scuba diver's use of selection criteria for assessing wetsuit using FEA model. *International Journal of Costume and Fashion, 18*(2), 45–64. https://doi.org/10.7233/ijcf.2018.18.2.045

Michaelson, D., Teel, K., & Chattaraman, V. (2018b). Assessing rock climbers' functional needs in climbing pants. *Clothing and Textiles Research Journal, 36*(4), 235–250. https://doi.org/10.1177/0887302x18783580

O'Sullivan, P. B., Dankaerts, W., Burnett, A. F., Farrell, G. T., Jefford, E., Naylor, C. S., & O'Sullivan, K. J. (2006). Effect of different upright sitting postures on spinal-pelvic curvature and trunk muscle activation in a pain-free population. *Spine, 31*, E707–E712.

Perry, A., & Lee, J. (2017). Satisfaction with current martial arts' uniforms and purchase intention of new uniforms. *Fashion and Textiles, 4*(1), 1–18. https://doi.org/10.1186/s40691-016-0085-6

Song, S. J., Beard, C. A., & Ustinova, K. I. (2015). The effects of wearing a compression top on trunk and golf club motions during golf swing. *Clothing and Textiles Research Journal, 34*(1), 48–60. https://doi.org/10.1177/0887302x15602096

Tian, B., Lyu, Z., Wang, F., Cui, H., Tung, T., & Cao, W. (2019). A design process for a female auto-racing suit. *The Journal of the Textile Institute, 110*, 1–12. https://doi.org/10.1080/00405000.2019.1682958

Ulkar, B., Kunduracioglu, B., Cetin, C., & Güner, R. (2002). Effect of positioning and bracing on passive position sense of shoulder joint. *British Journal of Sports Medicine, 38*(5), 549–552.

Wallace, L., Slattery, K., & Coutts, A. (2006). Compression garments: Do they influence athletic performance and recovery. *Sports Coach, 28*(4), 38–39.
Wheat, K. L., & Dickson, M. A. (1999). Uniforms for collegiate female golfers: Cause for dissatisfaction and role conflict? *Clothing and Textiles Research Journal, 17*(1), 1–10.
Zappala, J., Orrego, C., Boe, E., Fechner, H., Salminen, D., & Cipriani, D. J. (2017). Influence of posture-cuing shirt on tennis serve kinematics in division III tennis players. *Journal of Chiropractic Medicine, 16*(1), 49–53.
Zhang, J., Zhang, S., Lau, N., Yip, J., Yick, K.-L., Zhou, J., & Yu, W. (2019). Assessing user needs of senior women during yoga exercises to optimize the design criteria of sports bras. In J. Zhang (Ed.), *International association of societies of design research conference 2019*. Manchester Metropolitan University.