An Experimental Analysis of the Influence of Costume Design on the Freedom of Movement of Performers in Music Performances

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ABSTRACT Musical performance is not only an auditory art; costume design, as a visual and ergonomic component, directly affects the performer's stage image, expressive gesture, and technical stability. In contemporary performance spaces increasingly equipped with optical motion capture, wearable sensing, and electromagnetic tracking interfaces, the functional compatibility of costume structures with upper-limb movement has become an engineering-relevant design issue. This study quantitatively analyzes how different costume designs influence performers' freedom of motion in cello performance. Three costumes were designed: standard concert attire, performance costume with decorative shoulder structures, and high-necked long-sleeved dress. Twelve professional cellists completed standardized performance tasks under the three conditions. A three-dimensional motion capture system collected shoulder flexion, shoulder abduction, and timing deviation data, which were jointly analyzed with subjective comfort ratings. The results show that shoulder structure and sleeve configuration significantly affect upper-limb range of motion. Decorative elements most strongly restrict shoulder abduction, while high-necked long-sleeved design further reduces movement comfort and timing stability. The consistency between subjective ratings and kinematic data indicates that motion-capture-based ergonomic evaluation can provide a rigorous basis for stage costume design and for future wearable sensor integration in performance environments.

INDEX TERMS performance costume, motion capture, ergonomic design, electromagnetic sensing, human movement analysis

I. INTRODUCTION

MUSICAL performance is an art form that combines the two senses of sight and sound. Performers are not only able to communicate musical meaning to the audience presented in the play through hearing, but their physical movements, stage presence, and costumes are also a significant part of the performance art. In a variety of stage situations, including symphony concerts, solo recitals, and opera performances, costumes may do more than simply define the idea of character or contribute to an atmosphere of the period but also add to the visual interest. However, when costume design has too much visual impact and a too deeply pursued artistic expression, the constraints it sets on the performer's physical movements become more obvious. This is particularly true in string players, their motions are complex upper limbs. The freedom of movement in the shoulders, arms and wrists has a direct impact on the quality of sound production, technical execution and expression of music. As a low-pitched string instrument, cello requires a wide ranging motion in the right hand for bowing and frequent shifting of the left hand on the fingerboard, and therefore the flexibility of the shoulder joint has a direct impact on controlling intonation and variation of tone. Thus, studying the effect of stage costumes on the freedom of movement of the cellists is of significant importance.

The role of clothing in the movement of the human body has been examined in an organized manner within the branch of ergonomics. Studies on functional clothing and human motion adaptability have shown the great influence of clothing structural design on joint range of motion, muscle extension and overall flexibility. In the field of music performance, the technical realization of the performer's body movements, while that is not only the carrier, is also an important component of the artistic expression. This study is based on the relationship of the design of costumes of music performance and degree of freedom of body movement of performer. Based on the experimental methods, the changes in the shoulder joint range of motion, the accuracy of the time of performance and the subjective comfort are quantitatively analyzed under different clothing conditions.

The subjects of the research were selected as cellists, the three representative costumes of stage performances were designed, and a three-dimensional motion capture system was used to obtain the kinematic data, with the purpose of finding the specific mechanism of action of the clothing design effect on the degree of freedom of the body movement of the performer. The results of research can serve as the scientific basis for the functional design of music performance costumes and promote the organic unity of artistic expression and ergonomics, and can also provide the practical case for the introduction of dynamic ergonomics in clothing design education.

II. RELATED WORK

In the field of clothing science, discussions surrounding functionality, structural design, and ergonomics have extended to various professions and specific scenarios. To explore the potential limitations of clothing on limb movement, related research has laid the foundation for understanding the core issues of this study. Azonuche et al. [1] assessed the extent to which existing work clothes restrict joint range of motion, muscle extension, and overall flexibility; their research methods provide a reference for analyzing the quantitative impact of clothing on freedom of movement. Ugwu et al. [2] studied how university teachers integrate computer-aided design (CAD) and pattern-making techniques when teaching clothing structural design courses, emphasizing the core role of structural design in achieving clothing functionality. Nadia [3] found that the application of Richpeace software significantly improved students' pattern-making abilities. Students were able to complete pattern designs faster and more accurately, and also showed higher proficiency in pattern correction, grading, and other processes.

In specific research on clothing structure, the design and optimization of key parts such as sleeves are important directions for improving the wearer's mobility. Sleeves are one of the most complex parts of clothing structure, and their size prediction directly affects the fit and aesthetics of the garment. Li [4] solved the technical problem of automatic recognition and prediction of key sleeve size based on two-dimensional clothing images. Yan [5] explored how to innovatively apply the embroidery patterns on traditional Guangxi silk fabrics to modern leather clothing design, so as to expand the decorative language and cultural connotation of leather fashion. However, quantitative research on the influence of decorative elements on functionality still needs to be deepened. Torres et al. [6] pointed out that the structural method of clothing has a significant impact on heat transfer, and in some cases, its importance may even exceed that of the fabric itself. This shows that clothing structure directly affects the physiological state of the wearer in addition to physical properties (such as thermal and moisture comfort). Opoku et al. [7] took the clothing manufacturing industry in Kumasi, Ghana as an example to explore the understanding and application of artificial intelligence technology by local practitioners, as well as the challenges they face. Owodiong-Idemeko et al. [8] showed in teaching practice that zero-waste cutting can not only effectively reduce fabric consumption, but also stimulate students' innovative design thinking and break the traditional cutting mode. Bans-Akutey et al. [9] found that freehand cutting is still very common in Ghana, especially in the production of traditional clothing and personalized customization, and is favored for its flexibility, speed and the fact that it does not require drawing complex paper patterns. Ampofowah et al. [10] improved tailors' ability to effectively utilize African printed patterns through workshop intervention. Although the above studies have promoted the development of clothing science from multiple dimensions such as ergonomics, structural design and technical application, there is still a lack of research on the quantitative relationship between clothing design and the freedom of movement of performers in the field of performance arts, especially in the field of music performance. Existing studies mostly focus on the static aesthetics or basic functionality of clothing, while ignoring its potential interference with the technical movements of performers during dynamic performances. This paper focuses on the experimental analysis of the impact of music performance costumes on the freedom of movement of performers, aiming to fill the gap in the dynamic ergonomics evaluation of performance costumes through scientific experimental methods, and to provide data support and theoretical reference for the integration of art and function.

III. METHODS

A. EXPERIMENTAL CLOTHING DESIGN

Based on the physical characteristics of cello playing, this study designed three experimental garments with different structural features. The first garment is a regular concert costume, which adopts a standard shirt pattern, with a fitted cut, a regular shirt sleeve, and an armhole depth that conforms to basic ergonomic design. The fabric is a regular cotton blend material. The second garment is a performance costume with a decorative shoulder structure. Based on the regular pattern, a three-dimensional decorative structure is added to the shoulder. The decorative elements adopt a multi-layered gauze stacking design, extending to about 3 cm outside the shoulder peak, while the sleeve shape remains unchanged. The third garment is a high-necked long-sleeved dress, which adopts a fitted cut, with a high-necked design that fits the neck, long sleeves with tight cuffs, and a body length that extends to the knees.[11].

All three experimental costumes were made of black fabric to eliminate the potential influence of color on subjective evaluation. The costume sizes were individually adjusted according to the performers' body sizes to ensure a consistent basic fit. To control variables, the three costumes were kept consistent in terms of fabric type, sewing process, and lining structure, except for differences in design features. After the experimental costumes were completed,

a professional costume technician inspected the fit to ensure that the costume structure met the design requirements and had no obvious manufacturing defects. Before the formal experiment, two performers who were not part of the experimental group were invited to try on the costumes and conduct a pre-experiment. Based on the feedback, the details of the costumes were fine-tuned to ensure that they were comfortable to wear and suited to performance habits. The design process of the experimental costumes fully considered the actual needs of stage performance, and was both typical and comparable, laying a good foundation for subsequent experiments [12-13].

B. EXPERIMENTAL SUBJECTS

Twelve professional cellists were recruited to participate in the experiment, seven males and five females, between the ages of 22 to 38 years, with mean age of 27.3 years and SD of 4.2 years. All participants had over eight years of experience as professional trainers and currently worked in cello performances or teaching. This study was approved by the Ethics Committee of Tongji University, and was performed in accordance with the principles of the Declaration of Helsinki. The experimental procedure and precautions were explained to the subjects in details prior to the experiment and the all the subjects were made to signing informed consent forms. The professional backgrounds of the participants represented different styles of playing and styles of teaching, which helped improve on the generalizability of the research results. The experiment was controlled during the energetic periods of the participants in order not to influence their performance with the impact of fatigue [14].

C. INSPECTION PROCEDURE AND MEASUREMENT METHOD

The experiment was performed in a temperature and humidity controlled laboratory where the room temperature conditions were maintained at 24 $\pm$ 1 degrees Celsius and the relative humidity at 50 $\pm$ 5% to have a minimum effect of environmental factors on performance and comfort of clothing. Before the experiment, participants were notified of the task and reflective markers were placed on their bodies on the seventh cervical vertebra, acromion, lateral epicondyle of the humerus, radial styloid process, ulnar styloid process, and third metacarpophalangeal joint. A three-dimensional motion capture system, with 8 infrared cameras and a sampling frequency of 100 Hz, was used to obtain kinematic data of the upper limbs in performance. The system was calibrated prior to the experiment in order to obtain sub-millimeter spatial positioning accuracy to guarantee the data acquisition accuracy.

The experimental task was to play an etude of the cello played by a musician for about 60 seconds (3 times in total), and play it in a normal playing posture. The etude was chosen from a classic textbook, and its level of difficulty was at the moderate level, and all participants were familiar with the etude to exclude the effect of differences in technical proficiency on the experimental results. Each participant was required to complete the performance task wearing three different experimental garments with the order of garment wearing being randomized in order to eliminate the order effect. And after working on the performance task with each of the garments they were asked to rest for 5 minutes and complete a subjective comfort evaluation scale. The scale consisted of the use of the visual analog scale, with the range of scores from 0 to 10 where the higher the score the greater the comfort [15-16]. The scale measured four dimensions: shoulder comfort, arm comfort, overall comfort of freedom of movement and wearing comfort. Each dimension was accompanied by detailed textual descriptions of each dimension to help participants accurately interpret the evaluation criteria.

IV. RESULTS AND DISCUSSION

A. ANALYSIS OF SHOULDER JOINT RANGE OF MOTION

Motion capture data processing results showed significant differences in the flexion and abduction angles of the left and right shoulder joints among the three performers under three experimental clothing conditions. Table 1 lists the descriptive statistics of the range of motion of the left and right shoulder joints under different clothing conditions.

TABLE 1. Comparison of shoulder joint range of motion under different clothing conditions (unit: degrees)

Clothing type	Shoulder flexion maximum	Shoulder flexion average	Shoulder abduction maximum	Shoulder abduction average	Time proportion exceeding the limit angle threshold (right shoulder abduction, %)
Standard concert garment	78.2±5.2 / 78.9±5.4	45.0±4.0 / 45.4±4.2	42.5±4.7 / 42.1±4.9	23.9±3.4 / 23.5±3.6	12.3±3.1
Decorative shoulder garment	72.1±6.0 / 72.7±6.2	41.5±4.6 / 42.1±4.8	35.1±5.1 / 36.1±5.3	19.1±3.7 / 19.7±3.9	24.6±4.5
High-neck long-sleeve dress	68.5±5.7 / 69.3±5.9	39.2±4.3 / 39.8±4.5	31.3±4.8 / 32.3±5.0	16.5±3.5 / 17.3±3.7	31.2±5.2

As shown in Table 1, when wearing regular performance costumes, the performer's maximum right shoulder flexion angle was 78.2 degrees, with an average flexion angle of 45.0 degrees; the maximum abduction angle was 42.5 degrees, with an average abduction angle of 23.9 degrees. More importantly, under regular clothing conditions, the right shoulder abduction angle reached its limit threshold only 12.3% of the time, indicating that the performer could move freely most of the time, only approaching the clothing's limitations when a large bowing motion was required. When wearing decorative shoulder clothing, the maximum right shoulder flexion angle decreased to 72.1 degrees, and the maximum abduction angle decreased to 35.1 degrees, while the percentage of time reaching the limit threshold increased sharply to 24.6%, almost twice that of regular clothing. When wearing a high-necked long-sleeved formal suit, the maximum right shoulder flexion angle further decreased to 68.5 degrees, and the maximum abduction angle decreased to 31.3 degrees, with the percentage of time reaching the limit threshold reaching as high as 31.2%. This trend indicates that shoulder structure and sleeve design significantly impact the range of motion of the shoulder joint, particularly restricting the abduction of the right shoulder (bow arm), which directly affects the amplitude and force of bowing. Especially when playing technical passages requiring extensive bowing, decorative shoulders and high-necked long-sleeved dresses significantly increase the frequency with which the performer encounters the limitations of the clothing structure, thus interfering with the fluidity of the performance. In contrast, while the range of motion of the left shoulder is also restricted, the range of motion is slightly less than that of the right shoulder. This may be related to the fact that the left arm primarily performs flexion and rotation movements, requiring less abduction space. This phenomenon may be related to the kinematic characteristics of the shoulder joint: abduction requires sufficient space below the acromion, which is occupied by shoulder decorations or tight sleeves, thus restricting arm abduction; on the other hand, flexion involves more relaxation in the anterior part of the shoulder joint, where there is usually more space to accommodate clothing.

B. ANALYSIS OF THE ACCURACY OF PERFORMANCE TIME

Performance time deviation is an important indicator for the measurement of the accuracy of performance movements, which reflects the degree to which the movements of clothing interfere with the technical performance of a performer. Table 2 shows the statistical results of the deviation values of the time of performance under different clothing conditions.

TABLE 2. Comparison of performance time deviations under different clothing conditions (unit: seconds)

Clothing type	First performance	Second performance	Third performance	Average deviation
Regular concert attire	1.2±0.4	1.1±0.3	1.1±0.4	1.13±0.35
Decorative shoulder garments	1.8±0.6	1.6±0.5	1.5±0.5	1.63±0.52
High-necked long-sleeved dress	2.3±0.7	2.0±0.6	1.9±0.6	2.07±0.61

As shown in Table 2, with a standard concert attire, the average time deviation for three performances was 1.13 seconds, which is a relatively stable value. Under decorative shoulder clothing the average time deviation increased to 1.63 seconds (44.2% more than in standard attire). Under high-necked long-sleeved dresses, the average time deviation was 2.07 seconds for an 83.2% increase over standard attire. This result suggests that clothing restrictions on movement interfering with aid accuracy of performer's technique, causing the stability of the performer's control of timing of competition to decrease. From the point of view of the quality of the performance, the increase of the time deviation has an impact on the precision of the rhythm, and this, therefore, breaks the global structure of the music. Especially in ensemble situations, it may de-synchronize with the other parts with expressive rhythmic deviation is therefore not to be overlooked the influence of clothing on the timing of performance.

It is interesting to note that deviation of the time decreased progressively as the number of performances was increased. Under the condition of decorative shoulder clothes, deviation time was 1.8 seconds for the first performance and 1.5 seconds for the third performance, with a reduction of 16.7%. Under the condition of high neck long sleeve dress, the deviation was 2.3 seconds and 1.9 seconds for the first and third performance, respectively, which was decreased by 17.4%. This phenomenon implies that after frequent exposure to the same clothing, the performers are able to adapt partially to the limitations imposed by the clothing on movement and to mitigate the negative effect on their movement by changing their movement strategies. From a personal perspective, some of the participants demonstrated more rapid improvement in the process (adaptation), which might be related to the ability of motor co-ordination and psychological adjustment. In post-experiment interviews, some participants reported changing their posture and arm position consciously during their second performance to minimize contact with their clothing; this pre-emptive adaptation strategy was found to be helpful in alleviating the limitations of clothing. Future research might use surface elec-

tromyography (EMG) measurements to examine changes in muscle activity patterns during adaptation in order to better understand the mechanisms of adaptation.

C. SUBJECTIVE COMFORT EVALUATION AND ANALYSIS

Subjective comfort evaluation reflects the impact of clothing on performance from the perspective of the wearer's own feelings. This study used a visual analog scale (0-10 scale, with higher scores indicating greater comfort) to assess comfort across four dimensions: shoulder comfort, arm comfort, overall freedom of movement, and wearing comfort. It's important to note that these four dimensions have different conceptual emphases: "shoulder comfort" and "arm comfort" focus on assessing the structural restrictions imposed by clothing on specific body parts; "overall freedom of movement" measures the global interference of clothing with the complex movements required to perform a piece; and "wearing comfort" focuses more on the overall wearing experience, such as fabric feel and pressure distribution. Figure 1 presents the participants' subjective evaluation results of the three experimental garments.

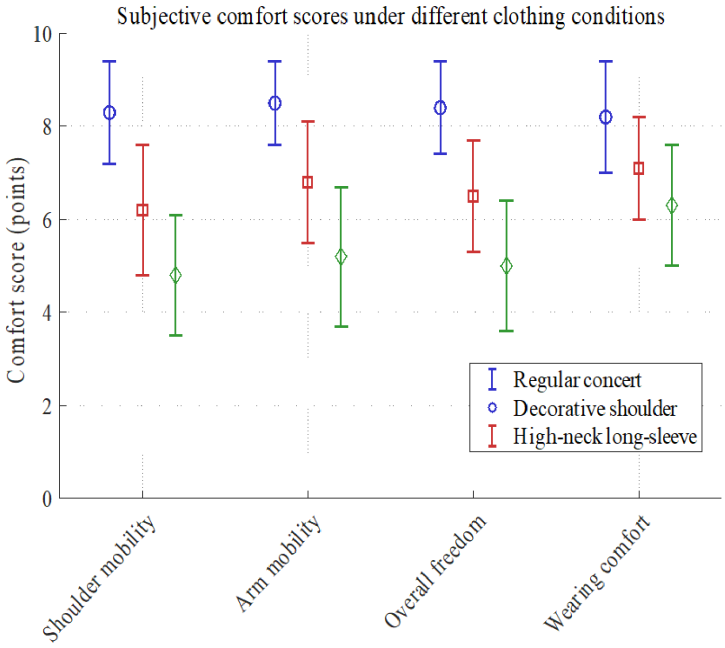

FIGURE 1. Comparison of subjective comfort scores under different clothing conditions (unit: points)

Regular concert attire obtained high grades in all the dimensions of evaluation; shoulder comfort (8.3 points), arm comfort (8.5 points), general freedom of movement (8.4 points) and wearing comfort (8.2 points), showing that the regular attire generally meets the needs of the performers for freedom of movement. Decorative shoulder attire, however, did experience a decline in shoulder comfort to 6.2 points (25.3% lower than regular attire), arm comfort to 6.8 points (20.0% lower), overall freedom of movement to 6.5 points (22.6% lower) and wearing comfort to 7.1 points (13.4% lower). High-necked long-sleeved gowns were also affected more and concept scored less in all areas: shoulder comfort to only 4.8 points (42.2% lower than regular attire), standard arm comfort to 5.2 points (38.8% lower), the freedom of movement to 5.0 points (40.5% lower) and the comfort of wearing it to 6.3 points (23.2% lower).

Subjective evaluation data and motion capture data demonstrated a high degree of consistency with corresponding relationship between decrease in shoulder range of motion comfort and reduction in abduction angle. In post-experiment interviews, participants generally reported that the decorative shoulder clothing significantly restricted elevation and abduction shoulder motions requiring the right hands to be adjusted to avoid contact with the structure of the clothing when playing high notes.

Based on a combination of objective measurements and subjective evaluations, this study found that the impact of costume design on the performer's freedom of movement is mainly manifested in three aspects. First, shoulder decorations greatly limit shoulder abduction, but have a much less pronounced effect on flexion, which is associated with shoulder structure and upper limb kinematics. Second, the extent of interference of costumes with performance timing accuracy is positively correlated with the extent of movement restriction; the lower the freedom of movement, the greater is the deviation of performance timing. Third, performers can adapt to costume restrictions within a certain amount of freedom but to some degree they can provide compensation for losses in function through movement strategy changes, which cannot however fully counteract the negative effect of costume design.

Examining the results of this study from the view-point

of clothing ergonomics, one finds that the creation of stage performance costumes should aim at the balance between artistic gold expression and functional requirements. Research on 19th-century opera costumes shows that the underarm gussets made a huge contribution to improving shoulder joint mobility, and this design concept can offer a reference for the improvement of modern stage costumes. The application of intelligent clothing technology in limb movement monitoring also gives technical support to the dynamic functional evaluation of the future performance costumes. For the cellists, shoulder movement is directly affecting the quality of bowing with the right hand; the design of costume should take into account the restriction in movement of shoulder joint through optimization of the structure and at the same time provide visual appeal. For example, the use of soft fabric or the introduction of the movable pleats in the shoulder decoration area, prevent the hard materials to cover the directly joint movement area; the sleeve design can refer to the tailoring of the functional sportswear, the purpose is to provide the needed freedom of movement while ensuring the aesthetics.

V. CONCLUSION

This study, for the first time, quantitatively analyzed the impact of musical performance costume design on the freedom of movement of cellists by combining 3D motion capture technology with subjective evaluation. It revealed the significant constraints of shoulder decoration and sleeve design on the range of motion of upper limb joints and the accuracy of performance timing. This research addresses the long-standing issue in the field of performance costumes—the lack of empirical data to support the relationship between artistic expression and functional requirements—and provides objective evidence for the functional improvement of stage costumes. However, the study has certain limitations: the sample size is relatively small and limited to cellists, failing to cover other instrument types and diverse stage scenarios; the experimental environment was simulated, differing from the psychological pressure and visual presentation effects of real performances. Future research could expand to include different instrument types and costume styles, introduce surface electromyography and psychophysiological indicators, explore long-term adaptation mechanisms, and promote the application of intelligent clothing technology in dynamic ergonomic evaluation to foster a deeper integration of performance arts and ergonomics.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by the Ethics Committee of Tongji University, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

AUTHOR CONTRIBUTIONS

Jiapeng Liu designed, collected and analyzed the data, and drafted the manuscript. Jiapeng Liu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Jiapeng Liu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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