Knitted linings for protective equipment against vibrations

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ABSTRACT – REZUMAT

Knitted linings for protective equipment against vibrations

Vibrations can affect the human body during everyday activities or in the workplace through various tools. It can occur at any point that comes into contact with a vibrating surface, including the hands (hand-arm vibration, HAV), the feet (foot-transmitted vibration, FTV) or the buttocks and back (whole-body vibration, WBV). The paper presents a group of knitted fabrics that could be used as linings for footwear or gloves, designed for personal protective equipment (PPE) in vibration environments. These fabrics have a single jersey tubular structure and were produced on a circular knitting machine with a small diameter and three stitch depths, made from functional yarns with good comfort properties. The knitted materials were tested using the free vibration method to measure their natural frequencies (Hz), as knowing these values helps to avoid resonance phenomena between the materials and the external vibrating system. The natural frequencies were measured in three directions (course, wale, perpendicular) and the results show that, for all variants, the natural frequencies measured in the perpendicular direction are four times higher than in the other two test directions. The fabrics made from Outlast natural fibre yarns have 30% lower natural frequency values than those made from synthetic yarns (Coolpass, Coolmax) or from natural-synthetic blended yarns (Dri-Release), which confirms the influence of the yarn type on the vibration behaviour of the materials. Coolpass, Coolmax and Dri-Release knits have comparable values of the natural frequencies, both in the course and wale test direction (41–48) Hz and (182–189) Hz in the perpendicular test direction. This type of knitted fabric, with low thickness and good extensibility, is suitable for anti-vibration equipment, e.g. in the field of dentistry, where it should be combined with a suitable antimicrobial and antibacterial treatment and a high level of comfort.

Keywords*: tubular single jersey, footwear linings, functional yarns, circular knitting machines, natural frequencies, vibrations*

Căptușeli tricotate pentru echipamente de protecție împotriva vibrațiilor

Vibrațiile pot afecta corpul uman atât în timpul activităților zilnice, cât și la locul de muncă, prin utilizarea diferitelor instrumente de lucru. Vibrațiile pot apărea în orice parte a corpului aflată în contact cu o suprafață care vibrează, inclusiv la nivelul mâinilor (vibrații mână-braț), al picioarelor (vibrații ale piciorului) sau al feselor și spatelui (vibrații ale întregului corp). Lucrarea prezintă un grup de tricoturi destinate căptușelilor pentru încălțămintea sau mănușile de protecție în medii vibratorii. Aceste tricoturi au structura glat tubular și au fost produse pe o mașină de tricotat circulară cu diametru mic, cu trei trepte de desime, realizate din fire funcționale cu proprietăți de confort superioare. Materialele au fost testate prin metoda vibrațiilor libere pentru măsurarea frecvențelor lor naturale (Hz), deoarece cunoașterea acestor valori contribuie la evitarea fenomenelor de rezonanță între materiale și sistemul de vibrații externe. Frecvențele naturale au fost măsurate în trei direcții (rând, șir, perpendicular), iar rezultatele arată că, pentru toate variantele, frecvențele naturale măsurate în direcția perpendiculară sunt de patru ori mai mari decât în celelalte două direcții de testare. Tricoturile obținute din fire din fibre naturale Outlast au frecvențe naturale cu 30% mai mici decât cele realizate din fire sintetice (Coolpass, Coolmax) sau fire în amestec naturale-sintetice (Dri-Release), confirmându-se astfel influența tipului de fir asupra comportării materialelor la vibrații. Tricoturile din firele Coolpass, Coolmax și Dri-Release au valori comparabile ale frecvențelor naturale, în direcția rândurilor și a șirurilor (41–48) Hz și valori de (182–189) Hz în direcție perpendiculară. Acest tip de tricot, cu grosime redusă și extensibilitate bună, este recomandat produselor antivibrații, de exemplu în domeniul stomatologiei, împreună cu un tratament antimicrobian și antibacterian adecvat și cu un nivel ridicat de confort.

Cuvinte-cheie: *glat tubular, căptușeli încălțăminte, fire funcționale, mașini circulare de tricotat, frecvențe naturale, vibrații*

INTRODUCTION

Vibration, regardless of its industrial origin, affects the human body, causes discomfort, impairs performance and can lead to various health problems [1]. Three main types of vibration are distinguished for workers who are exposed to aggressive vibration over a prolonged period: hand-arm vibration (HAV), foot-transmitted vibration (FTV) and whole-body vibration (WBV) [2–5]. From a clinical point of view, vibrations cause different manifestations that can be grouped into syndromes depending on the mode of action and degree of occupational exposure. In whole-body vibration exposure, very low-frequency vibrations 0–2 Hz can cause kinetosis, low-frequency vibrations 2–20 Hz cause rhythmic movements of organs in the pelvic and abdominal cavities and medium-frequency vibrations 20–200 Hz cause osteo-musculoarticular syndrome [6–9]. When workers are exposed to FTV by standing on platforms or equipment that vibrates, white feet/toes are observed, resulting in whiteness of the toes and tingling and numbness in the feet. Discomfort, pain or soreness is most severe when exposed to FTV in the range of 28–40 Hz and least severe below 10 Hz [5], [10]. In the case of HAV, the frequency range of 5.6–1400 Hz mainly affects the hand-arm system and leads to vascular disorders such as Raynaud's syndrome, which was first mentioned in 1862 by the physician Maurice Raynaud [11]. In addition, neurological disorders such as numbness, reduced tactile or thermal sensitivity and musculoskeletal disorders such as joint pain in the hand, elbow or shoulder, muscle weakness in the arm, tendonitis and reduced grip strength are also observed [12]. These negative effects can be mitigated by the use of personal protective equipment (PPE). However, a large proportion of these commercially available anti-vibration products contain insulating layers of materials such as polyurethane foam, air cushions, polymer gels and rubber which, despite their excellent anti-vibration properties, often offer low comfort due to poor moisture wicking, high stiffness or obvious thickness [13–20]. Alternatively, textile knitted structures offer several advantages, such as high flexibility, better comfort, and an optimal mass-to-volume ratio and have also proven to be superior in terms of comfort and environmental friendliness.

LITERATURE REVIEW

The international standard EN ISO 13753. Mechanical vibration and shock – Hand-arm vibration – Method for measuring the vibration transmission of elastic materials under loading by the hand-arm system, defines the resilient material used for the development of anti-vibration products as a material consisting mainly of foam with elastic properties or rubber and occasionally of a textile material [21]. Based on this framework recommendation, the well-demonstrated drawbacks of common elastic materials used for vibration-damping PPE [22–27] and the previous remarkable results obtained with spacer fabrics in technical applications such as seat cushions, anti-decubitus blankets or various industrial composites, several research groups have focused over the last decade on investigating the vibration-damping capacity of textile materials and the structural properties that correlate with this functionality. It has been shown that several raw material properties and process parameters must be met to develop a knitted fabric designed for a specific purpose. Many of these studies focused on identifying the parameters that define the functionality of the tested material, namely the damping capacity, but very few of them investigated the comfort requirements of anti-vibration PPE. The novelty of this ground-breaking research is the linking of these two areas, starting from the existing knowledge on functionality with a new focus on the comfort of PPE.

The comfort performance of anti-vibration materials should be considered in terms of the environmental conditions in which the PPE is used. Since cold is the main factor that increases the negative effects of vibrations on the human body, special attention must be paid to the *raw materials* selected to minimize these risks, starting with the analysis of the materials previously used. Natural fibres, such as cotton, are often used in anti-vibration gloves. There are several patents for them, but very few studies on their ability to reduce vibration transmission [22, 26, 28]. Synthetic fibres are the most commonly used raw material for knitted anti-vibration structures. Their damping performance has been investigated in numerous experiments, but the influence of the raw material on the vibration behaviour has rarely been analysed [23, 29–32]. For artificial fibres such as polyacrylonitrile and polypropylene, there are very few studies that have investigated their influence on the ability to dampen vibrations [29]. High-performance fibres such as Kevlar or Dyneema have been used in the development of anti-vibration gloves for specific applications where cut-resistant and fire-resistant properties are required [33]. In some models of anti-vibration gloves, para-aramid yarns or high-density polyethylene have also been used for the outer layer and various types of elastic yarns for the wrist band or backhand areas [22, 26–27, 34].

Fabric thickness is an important parameter for both cushioning capacity and comfort properties. Based on the fundamental theory of mechanics that for good vibration isolation it is necessary to reduce the dynamic stiffness of the isolator material for low resonant frequency values during vibration, it has been deduced that the use of thicker materials is highly recommended for this purpose. To achieve a relatively high thickness without compromising flexibility, dexterity and tactile sensitivity, some research has focused on achieving an optimal thickness for specific vibration isolation applications [23, 31, 35]. The influence of *fabric mass* per square meter on the natural frequencies of the vibration damping material is investigated for the first time by the authors in this paper, and no other studies on the influence of this parameter were found in the literature.

The damping performance of protection materials has been widely studied in the literature. Particular attention has been paid to *knitting technology*, especially spacer fabrics, which are frequently used in the manufacture of vibration-damping materials [35–37]. Recent tests with spacer fabrics specifically designed for vehicle driver seats showed good vibration isolation in the frequency range of 0–35 Hz, as it is known that low and medium frequencies have the strongest negative effects on human health [9, 38]. The *test direction* has a certain influence on the natural frequencies measured in all three directions: transverse, longitudinal and perpendicular. In most cases, the highest values were recorded in the vertical direction [29–30, 39, 40]. This was confirmed by testing seven commercially available anti-vibration gloves, which proved to be more effective against vibrations transmitted to the palm in the forearm direction (z-axis) than in the x- and y-directions [41]. It has been shown that the *tightness of the fabric*, a property of knitted fabrics that correlates with the machine stitch depth parameter, influences the natural frequency of the fabric. In particular, increasing stitch depth is associated with decreasing natural frequency values, which is reflected in a lower stiffness of the fabric [39].

MATERIALS AND METHOD

Knitted materials

A tubular single jersey structure was created from two types of 100% synthetic yarns, 150 den, with superior moisture transport, drying properties and prolonged heat retention on the body (Coolpass and Coolmax), one blended yarn of synthetic and natural fibres, 30/1 Ne, characterized by optimized moisture transport, drying, soft feel and comfort (Dri-Release) and one artificial yarn made from natural fibres, 30/1Ne, which offers temperature regulation through micro-encapsulated phase change materials embedded at fibre level (Outlast).

The knitting process was carried out on the circular knitting machine “Lab Knitter” 24E (Mesdan-Lab), with a diameter of 3¾ inches, 1 knitting system, 240 working needles, a negative feed system and a cylinder speed of 0 to 450 rpm. The knitting conditions were set by adjusting the stitch depths at three levels, while the yarn feed tension, take-down tension and cylinder speed were kept constant. The minimum and maximum values of the stitch cam division were determined in correlation with the machine gauge and the fabrics were defined as tight (3.0), medium (9.0) and loose (15.0). The fabrics were relaxed in dry condition and finished according to the standard EN ISO 6330 for textile testing. The mass per square meter (g/m^2) was determined according to EN 12127 and the fabric thickness according to ISO 5084 [42].

In this study, materials were tested against vibrations to characterize them as linings in protective footwear. The yarns used for these knitted fabrics are efficient in terms of moisture and thermoregulation, as the negative effects of vibrations on the human body are enhanced in cold environments [43, 44].

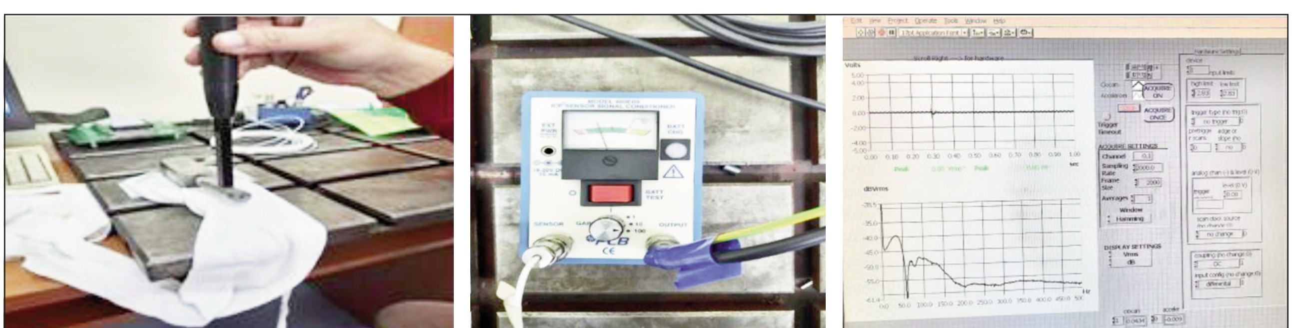
Testing method

A Piezotronics impact hammer was used as the dynamic exciter of the knitted material and the vibrations were measured with a PCB B52 Piezotronics accelerometer (figure 1, *a*). The signal was processed with a 6023 National Instruments data acquisition card (figure 1, *b*). To determine the natural frequencies of the system, Fast Fourier Transformation (FFT) was applied and the Spectrum Analyzer application of LabView 8.2 software was used (figure 1, *c*). Weft knitted fabrics behave differently in horizontal and vertical directions due to the particular way in which the needles, which knit the yarn across the width of the fabric, form the stitches. For this reason, the knitted fabrics were tested in the wale and course directions, as well as, in the perpendicular direction. Each measurement was repeated three times, mean values, standard deviations and the coefficient of variation (CV%) were determined for each test direction. The results show a CV of 14.1% in the course direction, 11.3% in the wale direction and 13.15% in the perpendicular one. The somewhat high CV values are justified by the fact that the experimental measurements for fabrics made from Outlast yarns are 30% lower than those for fabrics made from the other three yarns.

The curves generated with LabView 8.2 software are shown in figure 2. The frequency for each material and test direction was measured in the graphs from the first highest peak, which represents the natural frequency of the material.

RESULTS AND DISCUSSIONS

This study deals with the influence of yarns type on the natural frequencies of knitted materials, with the aim of achieving a PPE with higher comfort by using high-performance yarns. The measured natural frequencies of the knitted materials were analysed and their values were displayed, correlated with the main knitting parameters in order to draw the appropriate conclusions and define further research limits.



a *b* *c*

Fig. 1. Free vibration method for measuring the natural frequencies: *a* – piezoelectric hammer; *b* – data acquisition system; *c* – LabView Software

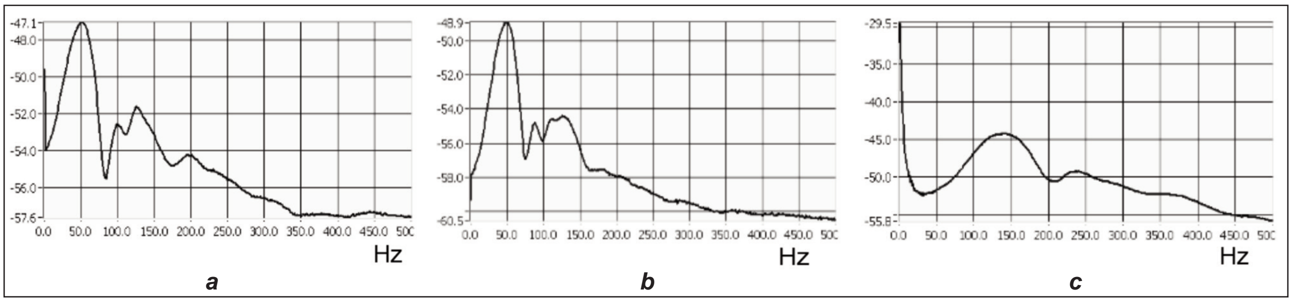


Fig. 2. Recorded values of the natural frequencies of the knitted material [40]: *a* – coursewise; *b* – walewise; *c* – perpendicular

The influence of yarn type on the natural frequencies of knitted materials

When analysing the data obtained, it was found that the Outlast fabrics, which are 100% viscose type, had the lowest values for natural frequencies in all three test directions and the Coolpass and Coolmax fabrics, which are 100% polyester, had the highest values for natural frequencies (figures 3). Dri Release fabrics, with a small percentage of 10–15% cotton, in addition to the predominantly polyester component, registered similar values with synthetic yarns, for perpendicular and coursewise directions (figure 3, *a* and *b*), even higher for the walewise (figure 3, *c*). The hypothesis regarding the influence of yarn type on the behaviour of knitted fabrics in the vibration environment is thus confirmed. It is therefore worth investigating blended yarns further to improve the comfort of products designed to protect against vibrations. The different behaviour of knitted fabrics made of different yarn types was confirmed by the analysis of weft knitted fabrics previously subjected to the same vibration tests [39, 45].

The influence of the fabric's thickness on the natural frequencies of knitted materials

The diagram in figure 4 shows that the natural frequencies of Coolpass fabrics increase with increasing thickness and do not decrease as expected. Similar values for the natural frequencies were measured for Coolmax and Dri Release knitted fabrics regardless of the thickness. With Outlast fabrics, the differences in the measured frequencies could not be correlated with the variation in their thickness.

One explanation for this behaviour could be that the knitted fabrics in the group studied have very low thicknesses 0.51–0.73 mm and the differences between them are insignificant.

The influence of fabric mass on the natural frequencies of knitted materials

The influence of fabric mass per unit area (g/m^2) on the natural frequencies was not investigated to date and no studies on the influence of this parameter were found in the literature. Although the tested

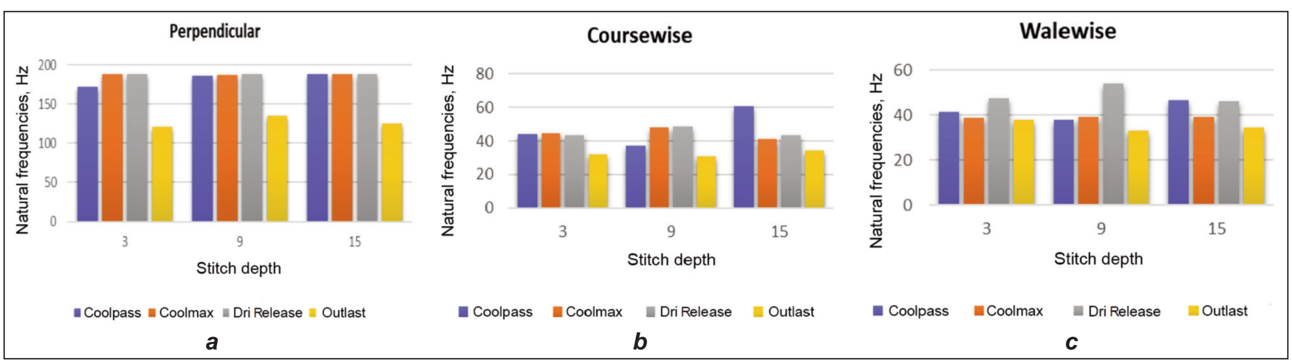


Fig. 3. Natural frequencies of knitted fabrics from different yarns: *a* – perpendicular; *b* – coursewise; *c* – walewise

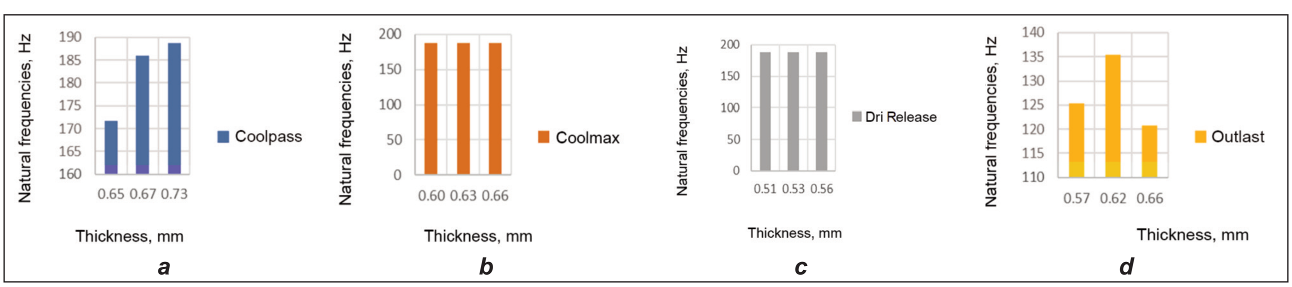


Fig. 4. Natural frequencies of knitted fabrics and the thickness: *a* – Coolpass; *b* – Coolmax; *c* – Dri-Release; *d* – Outlast

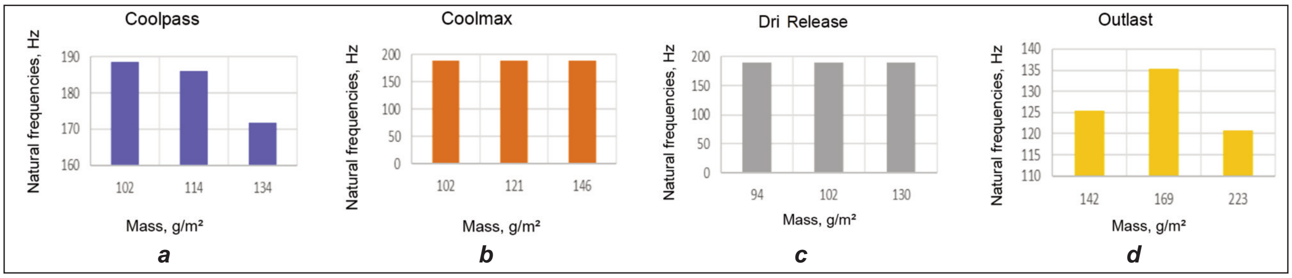


Fig. 5. Natural frequencies of the fabrics and the mass per unit area:
a – Coolpass; *b* – Coolmax; *c* – Dri-Release; *d* – Outlast

fabrics showed a significant increase in mass with decreasing stitch depth, the recorded frequency values could not be correlated with this parameter. The diagram in figures 5 shows that the natural frequencies of the Coolmax and Dri Release knitwear showed identical values regardless of the variation in the mass of the material. The range of values was between 94–146 g/m^2, but their behaviour is comparable, which led to the same conclusion that the most important influencing factor is the type of raw material and not the specific weight of the knitted fabric.

In the Coolpass knitwear, the increase in mass caused a decrease in the recorded natural frequencies. In the case of Outlast materials, the differences in the recorded frequencies could not be correlated with the variation in mass at all.

The influence of the test direction on the natural frequencies of knitted materials

Figure 6 shows that the frequency level for each of the four yarns fabrics, is comparable in the wale and course directions and that approximately four times higher values were measured in the perpendicular direction. The previous research demonstrated that the highest values of natural frequencies are recorded in the perpendicular direction and this indicates a higher stiffness of the materials in this direction of testing [29–30, 39, 40].

The values displayed show that the frequency levels for the three raw materials (Coolpass, Coolmax and DriRelease) are comparable in the course 40–75 Hz and wale 37–50 Hz directions, while the values in the perpendicular direction are around four times higher 186–190 Hz. Outlast knitted fabrics showed lower values in all directions, respectively 29–37 Hz in the row direction, 30–40 Hz in the wale direction and 116–140 Hz in the perpendicular direction.

The influence of stitch density on the natural frequencies of knitted materials

The tightness of the knitted fabric can be adjusted on knitting machines by the different positions of the stitch cam. The higher the division of the stitch cam, the longer the stitch length, the looser the knitted fabric and the lower the stitch density. When the recorded natural frequencies were analysed, it was found that they did not confirm the hypothesis put forward in the authors' previous studies, in the sense that the higher the NP value, the lower the recorded natural frequencies. For this group of knitted fabrics, the differences recorded as a result of the variation in stitch depth on the three levels were inconclusive in that

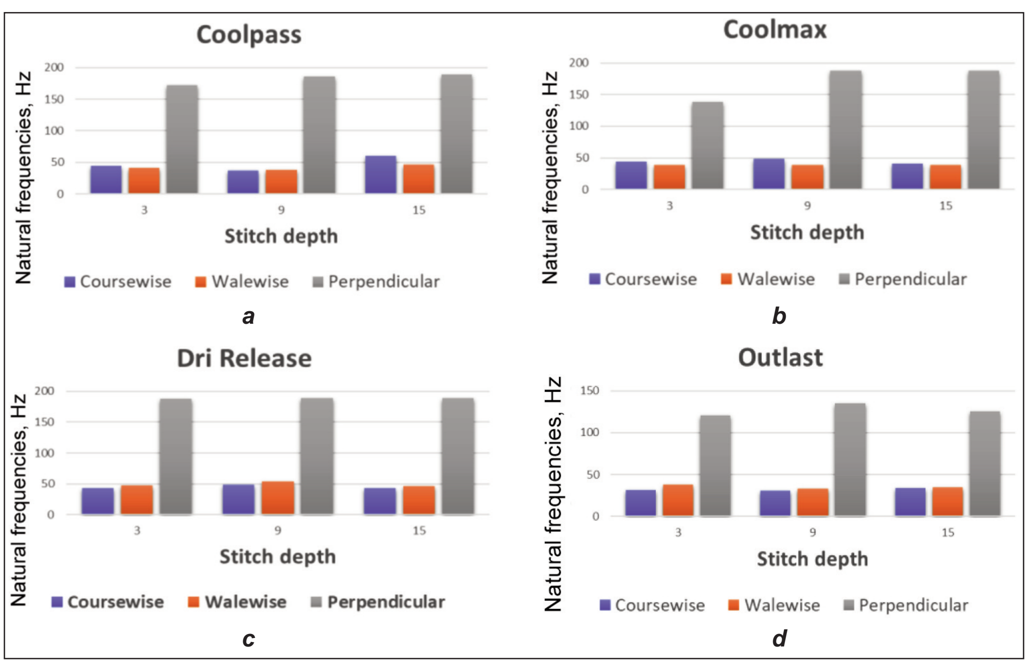


Fig. 6. Natural frequencies of the fabrics and the test direction: *a* – Coolpass; *b* – Coolmax; *c* – Dri-Release; *d* – Outlast

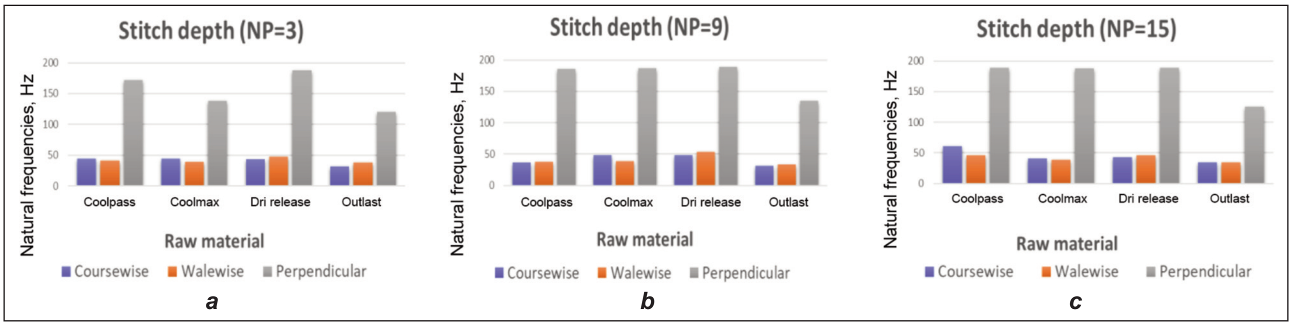


Fig. 7. Natural frequencies of the fabrics and the stitch depth values: *a* – stitch cam depth value 3; *b* – stitch cam depth value 9; *c* – stitch cam depth value 15

the values obtained for the same raw material were quite close to each other, with differences of 10–15 Hz and the increases or decreases in the recorded frequencies could not be correlated with the stitch depth value (figure 7).

CONCLUSIONS

The energy emitted in the form of vibrations from various electrical or mechanical sources and absorbed by workers can have a negative impact on their health and productivity at work and, with prolonged exposure, can lead to permanent occupational diseases.

One of the properties of materials relevant to a vibrating environment is their natural frequency, which provides information about their stiffness. The higher the measured natural frequencies, the stiffer the material.

The thickness and specific mass of the fabrics were investigated in this study and no correlation was found with the recorded natural frequencies, and this led to the conclusion that the type of yarns is the main influencing factor when it comes to knitted, very thin and stretchable linings as part of the overall construction of a PPE.

As the negative effects of vibrations increase in cold working environments, special attention must be paid to the comfort of fabrics by selecting the right yarns with excellent comfort properties. From this point of view, the use of synthetic-natural blended yarns that improve both the mechanics and comfort of protective materials is a worthwhile further research objective.

This research opens up new ideas for the development of materials that meet the dual requirements of PPE in terms of mechanical absorption of vibrations and adaptive comfort in different environmental conditions. The use of knitted fabrics for this purpose is a promising research direction, as today's knitting technology allows the development of materials with suitable physical properties such as weight, thickness, density and different raw materials.

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