Development of Pant-Type Harness with Fabric Air-Pocket for Pain Relief

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Abstract: Harnesses can be used in various applications, such as entertainment, rescue operations, and medical applications. Because users are supported on the harness for a long time, they should feel comfortable wearing the harnesses. However, existing commercial harnesses are uncomfortable to wear and cause continuous serious pain. Therefore, in this study, a new pant-type harness with a fabric air pocket to reduce the applied pressure on the body, especially in the groin, is proposed. Keeping this in mind, we have designed and developed the pant-type harness. In addition, we performed pressure and contact area measurement experiments using the harness developed, pressure sensor, and a human mannequin. Peak and mean pressures and contact areas near the groin and waist were measured in the experiments. From the results, when air is injected in the air pockets, the peak pressure and contact area near the waist increased, and the peak pressure near the groin decreased. This means that the pressure applied on the human mannequin near the groin reduces because of the increased contact area near the waist, which is achieved by multi-layered air pockets. In this study, we proposed the optimal design of a novel pant-type harness that can address the limitations of existing harnesses. The proposed harness can be used for a prolonged time in applications, such as virtual reality entertainment, rescue operations, and rehabilitation.

Keywords: ergonomic design; fabric air pocket; pain relief; pant-type harnesses; pressure distribution

1. Introduction

A harness is a looped restraint or support for fall protection. It can be used in applications such as virtual reality entertainment and performance to guarantee user safety [1]. A harness can also be used in assistance devices for rehabilitation, where patients can exercise safely, and for suspended working [2–4]. A conventional commercial harness consists of strap loops for the legs, a waist belt, and metal buckles. When users wear the harness, they feel activity restriction and severe pain due to the strap-type loops. Furthermore, most harnesses are similar in shape, even if they are considered for different types, applications, and environments. When users wearing strap-type harnesses are lifted, they feel uncomfortable because of the pressure generated by gravity on the contact area (pelvis and thigh). Several studies have shown that existing harnesses are uncomfortable for users [5–12]. Zwiener et al., who performed a suitable rescue-time experiment using a harness, found that 19% of the subjects asked to stop the experiment due to discomfort. However, detailed information on the discomfort point was not provided in this research [10]. Lee et al. studied the pressure while wearing commercial harnesses and found that pressure distribution causes discomfort, highlighting the need for the optimal design of harnesses to reduce pain [11]. They also found that the highest pressure...
points were the groin and perineum [12], which could be attributed to the anatomical structure of the human body. In particular, while hanging on the harness, the peak pressure was higher than standing. Based on these studies, a novel harness that provides comfort to the user was designed. In this study, we introduce a novel pant-type harness to improve the comfort by distributing the pressure generated by gravity to tissues near the waist, pelvis, and thigh. For this purpose, we make an assumption that by increasing the pressure near the waist, severe pain near the pelvis and thigh is reduced due to pressure distribution. Therefore, we designed and developed air pockets in the waist loops and injected air in them to increase the contact area between the waist and loops. In addition, pressure measurement experiments were performed using the proposed harness, a human mannequin, and a pressure measurement system.

2. Materials and Methods

2.1. Harness Design

Existing strap-type harnesses have straps at thighs to prevent users from falling after fastening waist straps. After prolonged usage of the harness or after performing dynamic motions, the pressure from the straps at the lymph nodes increases, eventually causing pain. The main aim of this study is to develop a harness that can support the body without causing severe pain. A pant-type harness without straps is designed and developed to measure the effect of pressure at the thigh based on the tightness at the waist. Figure 1 shows the developed novel harness, which introduces the outside, inside, front, back, and side views. Usually, commercial harnesses put less pressure on the thigh based on the tightness at the waist during contact with the user’s body because of the curved shape of the harness. Thus, we propose specially developed air pockets to increase the contact area of the harness and the body.

![Figure 1. Developed novel harnesses.](image)

2.2. Materials

The harness is equipped with air pockets to reduce the pressure exerted by it when it is worn. These pockets consist of two main parts: The outer shell and inner fillers. The outer material of the air pocket was polyurethane welding fabric, which was made of welding film coating on the nylon span fabric as shown in Figure 2. We used two different types of fillers. The first filler was nonwoven and consisted of polyester with high elasticity and high compressibility, containing EM 5D 40% and hollow fiber 7D 60% (800 g/m²). The other filler was a three-dimensional spacer fabric (690 g/m²) as shown in Figure 3. The air pocket prototypes had a different number of layers and sizes (Figure 4). The detailed specification of air pockets is given in Table 1. These pockets were fabricated using thermosetting sealing. Small air pockets were created at the front of the harness, while the others were at the back.
Figure 2. (a) Surface of the air pocket fabric and (b) surface of the other side.

Figure 3. (a) Surface and lateral surface of nonwoven filler, and (b) structure of three-dimensional spacer fabric filler.

Figure 4. (a) Different number of layers of air pocket, (b) 30 cm × 15 cm and (c) 50 cm × 15 cm size of air pockets.

Figure 5 shows the structure of the harness with air pockets. The harnesses were classified on the basis of the air pocket position: the single set harness had air pockets only on the front, and the double set harness had air pockets on the front and the back.

Figure 5. Positioning of air pockets in the harness. (a) Front side, (b) harness and air pockets and (c) back side.
Table 1. Layers and size information of air pocket.

| Layer   | Size of Air Pocket |
|---------|--------------------|
| 2 layers| 30 cm × 15 cm      |
|         | 50 cm × 15 cm      |
| 4 layers| 30 cm × 15 cm      |
|         | 50 cm × 15 cm      |

2.3. Sensors

In the experiment, a pressure sensor (64 sensor cells, Pliance sensor strap, sensor S2148, Novel GmbH, Germany) was used to measure the pressure from the harness. Table 2 shows the specification of sensors, which consists of 64 sensor cells, controller, and wires. Figure 6a shows the strap-type pressure sensor and controller, which can be easily attached to the harness to measure pressure. The sensors were located on the inner thigh and the front and rear side of the waist to measure the pressure during wearing of the harness as shown in Figure 6b.

Table 2. Specification of pressure sensor.

| Sensing Area  | Pressure Range | Sensitivity | Number of Sensor Cells |
|---------------|----------------|-------------|------------------------|
| 160 mm × 40 mm| 15 ~ 600 kPa   | 1 sensor cell/cm² | 64                     |

2.4. Experimental Setup

We assume that the contact between the waist and harness affects the pressure at the thighs (lymph nodes). If the contact area between the waist and harness increases, the pressure at the thigh decreases because of the distribution of the pressure to the waist. Therefore, we observe the variation of the contact area and pressure by the experimental variables in the standing posture. To prove this assumption, we considered four types of posture: standing, loaded, back-loaded, and front-loaded. The experiments were performed using a mannequin (Model KM-12, Seonyu Inc., Korea), shown in
Figure 7a. The height and weight of the mannequin are 1.88 m and 30 kg, respectively. Air charging of the air pockets was also included as a variable. Figure 7b shows the postures used in the experiment. The number of air pockets was controlled to observe the pressure distribution on the waist and leg.

Figure 7. (a) Mannequin wearing the harness and (b) the four postures in the experiments.

3. Results

To verify the assumption regarding pressure distribution, the contact area needs to be considered. Figure 8 shows the contact area between the harness and the waist. We assumed that the untreated condition means that the air pockets are not equipped into the harness. In this condition, all of the contact areas are 0 cm². From the experimental results, we measured the contact area for the standing posture as 0 cm² for the air pocket without air charge. We performed the experiments and measured the results of four different conditions (single set/two-layered, double set/two-layered, single set/four-layered, and double set/four-layered). For the air-charged air pockets, the contact area increased regardless of the posture. Figure 8a shows the contact area distribution, which was measured using the pressure sensor. The contact area for the two-layered double-set harness in the loaded posture was 52 cm², which was the largest (Figure 8b). Among all postures, the loaded posture had the largest contact area on average. The contact area in the front-loaded posture was smaller than that in the loaded posture (Figure 8c). The contact area in the back-loaded posture for the four-layered double-set harness was 7 cm², which was the smallest (Figure 8d). Except for the two-layered double-set harness with air-charged air pocket, the contact area was the smallest in the back-loaded posture. Except for the two-layered double-set harness with air-charged air pocket, the contact area was the smallest in the back-loaded posture. The results from the loaded posture had the biggest contact area through the whole posture, we focused on the loaded posture to observe the relationship between pressure and contact area.

Figure 9 shows the mean and peak pressures on the waist for each position. The highest peak pressure was observed in the two-layered double-set harness, regardless of the posture. The highest peak pressure, 81 kPa, was measured in the loaded posture. The peak and mean pressures in the loaded posture were larger than those in other postures. In four-layered harnesses, the peak pressure increased with the number of air pockets. This was particularly observed for the loaded posture. However, the peak pressure in four-layered harnesses, 68 kPa, was the largest in the front-loaded posture. The mean pressures were measured to be less than 10 kPa. In addition, the pressure in the harnesses without the air-charged air pockets was less than that in the harnesses with air-charged air pockets, especially the mean pressure.
of the air pockets was also included as a variable. Figure 7b shows the postures used in the experiment.

Figure 7. (a) Mannequin wearing the harness and (b) the four postures in the experiments.

Figure 8. Contact area measurements for (a) standing, (b) loaded, (c) front-loaded and (d) back-loaded postures.

Figure 9. Cont.

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The contact area and pressure in the loaded posture were considered to validate the suggested assumption because these values were the largest during the experiment. Moreover, the results need to be considered for not only the waist but also for the leg. Figure 10 shows the contact area distribution and results obtained in the loaded posture. Unlike the contact area on the waist, the contact area on the leg decreased depending on the charge of the air pockets and the number of air pocket layers and sets. The largest decrease was 13 cm², which was observed in the two-layered single-set harness. The four-layered double-set harness had the smallest contact area: 59 cm² for an air pocket without air charge and 55 cm² for an air-charged air pocket. In addition, when the number of air pocket sets was increased, the contact area decreased, as shown in Figure 10. For the two-layered double-set harness, the contact area was 60 cm², while for the two-layered single-set harness, it was 72 cm².

Figure 11 shows the pressure distribution and peak/mean pressures on the leg in four different conditions (single set/two layered, double set/two-layered, single set/four layered, and double set/four layered). The results show that the pressures decreased with the increase in the number of air pocket sets and layers, as expected. For two-layered harnesses, the largest peak pressure, 214 kPa, was measured for the single-set. Moreover, the four-layered double-set harness showed the lowest peak pressure, 95 kPa.

When the number of air pocket sets and layers was increased, the peak pressure decreased, as shown in Figure 11c. For the two-layered single-set harness, the peak pressures were 214 kPa and 178 kPa without and with air-charged air pockets, respectively. For the two-layered double-set harness, the peak pressures decreased to 160 kPa and 129 kPa without and with air-charged air pockets, respectively. In addition, for the four-layered single-set harness, the peak pressures were 134 kPa and 126 kPa without and with air-charged air pockets, respectively. The results for mean pressure followed a trend similar to peak pressure.
Figure 10. Contact areas on the leg during loaded posture: (a) contact area distribution and (b) measured contact areas.

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4. Discussion

In this study, we developed a novel pant-type harness with a fabric air pocket to decrease the user pain caused by gravity. To validate the reduction in pain, we performed pressure measurement experiments using the developed harness, pressure sensor, and human mannequin. The results show that the pressure applied near the groin of the human mannequin decreased because of the increased contact area near the waist (achieved by multi-layered air pockets). In addition, the results show the relationship between pressure on the waist and leg at the loaded posture. Using the developed harness, the peak and mean pressures on the leg were reduced to 90 kPa and 10 kPa, respectively. From the results of our study, when the peak pressure on the waist increased, the peak pressure on the leg decreased. Figure 12a shows the relationship between peak pressures on the waist and leg, while Figure 12b shows the relationship between mean pressures on the waist and leg.
was 126 kPa. This value reduced by more than 25% to 93 kPa by using the four-layered double-set harness, while Figure 12b shows the relationship between mean pressures on the waist and leg. This result indicates that if the peak pressure on the leg decreased, the peak pressure on the waist decreased. Furthermore, pant-type harnesses can reduce the pain because the peak pressure on the waist decreases. For instance, in Figure 13a, the peak pressure on the leg in two-layered double-set harness decreased. For the four-layered double-set harness without air-charged air pockets, the peak pressure was 60 kPa. However, the peak pressures were 134 kPa and 129 kPa without and with air-charged air pockets, respectively. For the two-layered single-set harness, the peak pressures were 214 kPa and 178 kPa without and with air-charged air pockets, respectively. In addition, for the four-layered single-set harness, the peak pressures were 134 kPa and 129 kPa without and with air-charged air pockets, respectively. In Figure 12b, the mean pressure on the leg was higher than that on the waist. This is due to the curved shape of the waist, and therefore, the air pocket was not as well attached to the waist as to the leg. Because of this poor contact with the waist, the pressure was not acted on the waist, causing lower mean pressure on the waist. Nevertheless, as mentioned above, the existence of an air pocket at the waist significantly reduces the pressure on the leg, which is of great significance for the development of the new type of harness.

The relationship between the contact area and peak pressure can be observed more clearly for the two-layered harnesses than that for the four-layered harnesses. In Figure 13a, for the two-layered single-set harness, the contact area on the waist was 36 cm² and the peak pressure was 60 kPa. However, both the contact area and peak pressure increased to 52 cm² and 81 kPa, respectively, for the two-layered double-set harness. This is because the air pocket set doubled, increasing the contact area with the body. If the number of layers was changed from two to four, both the contact area and pressure decreased. For instance, in Figure 13a, the peak pressure on the leg in two-layered double-set harness was 126 kPa. This value reduced by more than 25% to 93 kPa by using the four-layered double-set harness, as shown in Figure 13b. This shows that the decrease in contact area causes a decrease in peak pressure. Therefore, the air pocket layers on the waist and leg can reduce the pain because the pressure decreases while wearing the novel pant-type harness.

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From the results of our study, when the peak pressure on the waist increased, the peak pressure on the leg decreased. Figure 12a shows the relationship between peak pressures on the waist and leg, while Figure 12b shows the relationship between mean pressures on the waist and leg.

For the four-layered double-set harness without air-charged air pockets, the peak pressure difference was about 41 kPa (99 kPa for leg and 58 kPa for waist). This means that the developed pant-type harnesses can reduce the pain because the peak pressure on the waist decreases. Furthermore, if air is injected into the air pocket, the peak pressures on the waist and leg are affected. The peak pressure difference between the two-layered single-set harness with and without air-charged air pockets on the waist is about 36 kPa (214 kPa without air charge and 178 kPa with air charge). This means that the peak pressure decreased by injecting air into the air pocket. All other cases show similar results. This result indicates that if the peak pressure on the leg decreased, the peak pressure on the waist increased. In Figure 12b, the mean pressure on the leg was higher than that on the waist. This is due to the curved shape of the waist, and therefore, the air pocket was not as well attached to the waist as to the leg. Because of this poor contact with the waist, the pressure was not acted on the waist, causing lower mean pressure on the waist. Nevertheless, as mentioned above, the existence of an air pocket at the waist significantly reduces the pressure on the leg, which is of great significance for the development of the new type of harness.
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![Graph](image1)

**Figure 12.** (a) Peak and (b) mean pressure relationship between waist and leg.

The relationship between the contact area and peak pressure can be observed more clearly for the two-layered harnesses than that for the four-layered harnesses. In Figure 13a, for the two-layered single-set harness, the contact area on the waist was 36 cm² and the peak pressure was 60 kPa. However, both the contact area and peak pressure increased to 52 cm² and 81 kPa, respectively, for the two-layered double-set harness. This is because the air pocket set doubled, increasing the contact area with the body. If the number of layers was changed from two to four, both the contact area and pressure decreased. For instance, in Figure 13a, the peak pressure on the leg in two-layered double-set harness was 126 kPa. This value reduced by more than 25% to 93 kPa by using the four-layered double-set harness, as shown in Figure 13b. This shows that the decrease in contact area causes a decrease in peak pressure. Therefore, the air pocket layers on the waist and leg can reduce the pain because the pressure decreases while wearing the novel pant-type harness.

![Graph](image2)

**Figure 13.** Relationship between the contact area and pressure on the leg and waist of (a) two-layered and (b) four-layered harnesses.

5. Conclusions

In this study, the proposed pant-type harness can address the limitations of existing harnesses and can be applied for prolonged usage in applications, such as virtual-reality entertainment, rescue operations, and rehabilitation. In addition, the developed harness can be used to exercise a variety of sports. The results obtained by the proposed harness also can be used for further study and they can be applied in order to develop a more comfortable harness.

**Author Contributions:**

Writing—original draft, D.N. and B.A.; data curation, J.K. and M.K.; formal analysis, M.K., B.A.; writing—review & editing, J.K. and B.A.

**Conflicts of Interest:**

The authors declare no conflict of interest.
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