A knitted smart sneaker system based on piezoresistive strain sensing for stride counting

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ABSTRACT – REZUMAT

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Currently, smart shoes are not as common as other wearable devices such as fitness trackers or smartwatches. However, with the continuous improvement in sensor and IOT technologies, it is expected that shoes with smart capabilities will catch up with the other popular wearables. The emergence of 3D knitting and its subsequent application in footwear manufacture has revolutionized the shoe manufacturing process. The use of knitwear allows for shoe parts such as the upper or the sole (insole, Strobel sole, midsole and/or outer sole) to be tailored with specific areas having different characteristics and providing different functions with low production effort. This study presents the design and manufacture of a knitted smart sneaker for cadence mensuration. The specified part of the sneaker is knitted with silver-plated polyester yarn to serve as a strain sensor. During the weight-bearing and release phases of the foot, while walking, this strain sensor is stressed and relaxed by this oscillatory phenomenon thus allowing footstep data to be measured. Stride estimate tests were carried out and the results established that strides taken by a user can accurately be correlated to the readings of the system. This study is the first to develop a smart shoe-sensing system where the sensor is inherently embedded within the shoe upper.

Keywords: *step counting, smart wear, knitting technology, strain sensor, textiles*

Un sistem inteligent de încălțăminte sport tricotată bazat pe senzorul piezorezistiv al deformării pentru numărarea pașilor

În prezent, pantofii inteligenți nu sunt la fel de obișnuiți ca alte dispozitive portabile, cum ar fi trackerele de fitness sau ceasurile inteligente. Cu toate acestea, odată cu îmbunătățirea continuă a tehnologiilor senzorilor și IOT, este de așteptat ca pantofii cu capacități inteligente să ajungă din urmă celelalte dispozitive purtabile populare. Apariția tricotării 3D și aplicarea sa ulterioară în fabricarea de încălțăminte a revoluționat procesul de fabricare a pantofilor. Utilizarea tricotajelor permite ca părți ale încălțămintei, cum ar fi căptușeala sau talpa (branț, talpă Strobel, talpă intermediară și/sau talpă exterioară) să fie realizate cu zone specifice, având caracteristici diferite și oferind diferite funcții cu un efort de producție redus. Acest studiu prezintă proiectarea și fabricarea de încălțăminte sport inteligentă tricotată pentru măsurarea cadenței. Partea specificată a încălțămintei sport este tricotată cu fire de poliester acoperite cu argint pentru a servi drept senzor de tensiune. În timpul fazelor de susținere a greutății și de eliberare a piciorului în timpul mersului, acest senzor de tensiune este stresat și relaxat de acest fenomen oscilator, permițând astfel măsurarea datelor de pas. Au fost efectuate teste de estimare a pasului și rezultatele au stabilit că pașii făcuți de un utilizator pot fi corelați cu precizie la citirile sistemului. Acest studiu este primul care a dezvoltat un sistem inteligent de detectare a încălțămintei inteligente, în care senzorul este încorporat în mod inerent în căptușeală.

Cuvinte-cheie: *numărarea pașilor, încălţăminte inteligentă, tehnologie de tricotare, senzor de tensiune, textile*

INTRODUCTION

According to anthropological evidence, the wearing of footwear began approximately 40,000 years ago [1]. From simple open-toe sandals in the early years, footwear has since evolved into more complex items of fashion. Footwear has been classified into different many categories. These include but are not limited to classes based on gender – ladies' and men's, occasion of wear – casual ladies' shoes, casual men's shoes, and type of activity – running shoes, etc. [2].

Other classifications include the type of material used such as leather shoes, and canvas shoes as well as age-based classes – children's shoes and adult shoes. There also exist sports shoe classes, such as a running shoe, basketball shoes, soccer shoes, American football shoes, baseball shoes tennis shoes etc. The terms sneakers/kicks/flats/trainers are also used to describe a certain category of shoes primarily designed for sports or other forms of physical exercise, but which are now also widely used for everyday casual wear. Conventionally, a shoe describes an item of footwear intended to protect and comfort the human foot. Shoes are also used as an item of decoration and fashion.

Generally, shoe manufacturing requires footwear uppers to be manufactured with multiple separate components, requiring multiple individual sub-assemblies and seams. The emergence of 3D knitting and its subsequent application in footwear manufacture has however revolutionized the shoe manufacturing process. Flat-knitted shaped uppers refer to the upper which are produced by flat knitting machines [3]. A knitted shoe upper is advantageously devoid of any sewn seams and does not require any manual post process in terms of cutting or sewing to create the dimensional shape [4].

The developments in knitting technology allow products such as a shoe upper or a sole of a shoe, such as an insole, Strobel sole, midsole and/or outer sole to be embedded with different characteristics at specified areas to provide different functions with low production effort [5]. The embeddable properties may include bending, stretching, air and water permeability, thermal conductivity, thermal capacity, moisture absorption, static friction, abrasion resistance, hardness, thickness etc.

With the improvement in living standards, people have a higher demand for the comfort of sportswear, such as lightweight, functional and other decorative effects [6]. The shoe upper plays a wrapping and supporting role for the foot in the process of walking and sports. It not only helps to keep warm while also providing a guarantee of safety and stability [7].

Designing functionally adequate footwear requires an understanding of the dynamic biomechanical behaviour of the foot during locomotion [8]. Footwear manufacture using flat-knitted shaped uppers presents opportunities for the use of materials with excellent properties and also with a high degree of formability. Knitting is carried out with dyed yarns thereby requiring no dying of finished product and thus delivering plentiful colours and pattern structure variability. It also provides effective ways to minimize production complexities and times, cut back on environmental pollution [9] and improve product integrity have attracted massive research attention.

With the development of IOT technology, conventional articles are all equipped with smart functionalities, from chairs [10], beds [11], and caps [12] to underwear [13]. However smart shoes tend to lag in terms of volume and popularity among these smart device craze. Many smart shoe researches directed at physical activity monitoring however exist in the literature [14]. Nonetheless most if not all are based on insole sensing systems [15, 16]. Therefore to the best of our knowledge, this is the first smart shoe walking cadence monitoring system that is integral to the shoe itself rather than the insole or footwear attachments.

The main functionality of this proposed smart sneaker is stride counting. Even though similar functionalities have been referred to as step counting, the use of the term step counting is a misnomer as only one foot was engaged in the tests conducted. The measurement of step or stride counting is important for so many reasons. It has been scientifically proven that humans routinely alter their walking paces to adapt to functional goals and meet physical demands [17]. Studies have also hinted that damage to the central nervous system oftentimes results in irregular modulation of the pace of locomotion and increased risk of falls [17].

According to a study by [18], individuals who took 12,000 steps a day possess a 65% lower risk of dying compared to individuals who only took 4,000. Higher step counts were also linked with decreased rates of death from cardiovascular disease [19] and cancer [20]. These benefits were consistent across age, sex, and race groups. There is thus overwhelming evidence supporting the need for tracking steps taken as a means of goal setting and encouraging more people to take more steps considering its immense health benefits.

EXPERIMENTAL

Materials and methods

The STOLL CMS530 E7.2 computerized flat knitting machine was selected to produce the flat-knitted shaped uppers. Materials used for the sneaker upper include silver-plated yarns purchased from Qingdao Hengtong X-Silver Speciality Textile Company; nylon DTY and covered elastic yarn from Zhejiang Jinqi New Material Tech. Co., Ltd.; and connecting cables purchased online from Tmall.com (figure 1).

Fig. 1. Photos of: *a* – smart sneaker with connection cable; *b* – signal acquisition and processing unit

Smart sneaker cadence system

The test interface is presented in figure 2; it is enabled with a panel to enter the type of test and signal display range and the electrical resistance of the sensor. There is also a start button, a pause/resume button and a replay button.

The software has the capability of automatically detecting the peak change in resistance over time, information which corresponds to a single step and is automatically recorded and saved in an Excel format strip-chart for further analysis. The smart sneaker connects to a signal processing unit (KTC electro-box) described in our previous studies [21, 22].

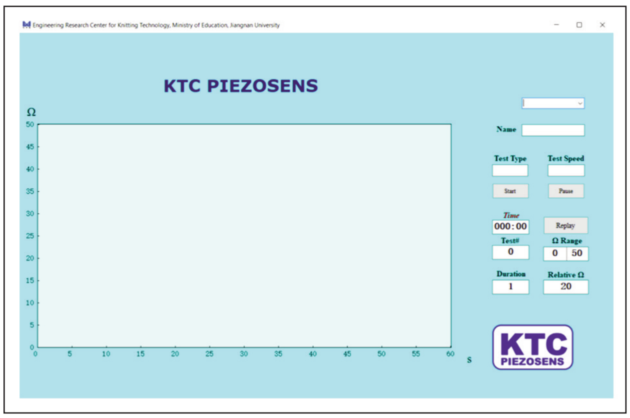

Fig. 2. Stride counting display interface

The system works such that deformation of the loop structures within the textile fabric (shoe upper) causes a change in resistance of the conductive section and is sensed by the basic circuitry in the electro-box. The indexes measured include steps per minute which is the number of steps taken per minute while walking corresponds to peaks shown in the interface.

User trials – stride counting experiments

Stride count trials were carried out and compared with a wrist-worn fitness tracker. Three main walking activities were used namely normal walking, and walking up and down seven-tier stairs. With regards to normal walking activity step accumulation within an epoch of one minute was measured. With the stair climbing and descending, the counting was done when the volunteer reached the summit and the foot of the stairs respectively.

Stairs climbing has been associated with several health benefits [23] including boosting cardiovascular health by improving blood circulation and enhancing good cholesterol levels in the body. Likewise, stair climbing has the possibility of allowing the individual to attain their fitness goals without the need for any major equipment or special training.

RESULTS AND DISCUSSIONS

The human foot acts in concert with the rest of the body during standing and movement. It provides man with his most effective physical contact with the environment and is especially responsible for the successful regulation of initial and final contact of the body with the ground.

Muscles, tendons, and ligaments run along the surfaces of the feet, allowing for the complex movements needed for motion and balance. During movement, the extensor digitorum brevis works in unison with other muscles to raise the toes off the ground when walking [24].

The human walking cycle can be partitioned into two main phases viz stance phase which occupies about 65% and swing phases – about 35–40% [25]. The stance phase (weight-bearing phase) is used to describe the period where the foot under consideration is in contact with the ground [26] while the swing phase in turn describes the period when the foot leaves the ground [27].

During the weight-bearing phase of ambulation, the sensor is stressed as the midfoot is flattened (instep girth expansion) [28] and therefore a change in resistance occurs. The swing phase which follows releases the stress on the sensor and so this recurrent action is used in computing the cadence of the user. From the wear tests carried out, it can be seen that the sneaker can satisfactorily estimate step counts over time.

The results of the three walking activities are shown in table 1. Within a time of 60 seconds and covering a distance of 43 meters, 28 strides were recorded during normal walking. Walking tests on seven-tier stairs were also carried out and within a time of 8 seconds, an average of 5 strides were recorded. The same values of 5 strides were recorded during the descent activity too.

The terms step counts or step accumulated per minute and cadence have been widely used interchangeably across literature over time. Both Dall et al. [29] and Stansfield et al. [30] however hint that this practice cannot be accurate. "True cadence" is the rate of stepping during the period of stepping. "Step accumulation" is the number of steps within an epoch of time (e.g. 1 minute) [29]. In the context of this manuscript, stride counts or stride accumulated per minute is most appropriate since only one foot was engaged in the tests conducted.

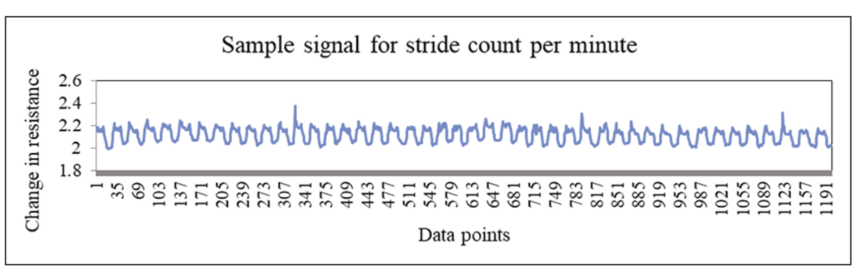

Fig. 3. Determination of strides from a sample walking data

Table 1

STRIDE COUNTING ACTIVITIES AND RESULTS				
Walking activity	**Number of steps**		**Distance (m)**	**Time (s)**
	AVG	**SD**		
Normal walking	28	2.08	43	60
Walking down stairs	5	0.6	7 tier stairs	8.0
Walking up stairs	5	0.6	7 tier stairs	8.0

This is corroborated when an attempt was made to compare the step-counting results with the commercially available wristband activity tracker. Within the same walking activities over the same periods, the commercial tracker recorded what it describes as average step counts of 88 steps for normal walking and 8 steps for climbing and descending stairs respectively compared to our device's 28 and 5, 5 respectively. This has discouraged any attempt to compare the device's output with other devices as information on computation algorithms and mechanisms of the other devices are dissimilar and or not known.

Sensing unit Repeatability / Stability / Durability / Aging

Sensor durability describes the capacity of flexible strain sensors to sustain steady electrical functionality and mechanical connection under long-term dynamic cyclic elongation cycles [31]. This property can also be referred to as stability in the short term, while it is described as ageing in the long term. Cronbach's alpha coefficient was thus applied to estimate these properties. By using four test results conducted within three weeks in the computation, high reliability was realized with normal walking accounting for α = 0.87, α = 0.92 for walking down the stairs and α = 0.88 for stair climbing respectively.

CONCLUSIONS

The study presented for the first time a shoe-based step counting system, where the sensor is inherently embedded in the shoe upper. The sneaker can measure stride count or stride accumulation per minute when tested using some walking activities.

The use of the term step counting is a misnomer as only one foot was engaged in the tests conducted. The authors therefore found no strong basis to compare the stride outcomes with wrist-worn or related activity trackers as there are disparities in mechanisms and the algorithms for these devices are also unknown.

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