A Wearable Airbag to Prevent Fall Injuries

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***Abstract*—We have developed a wearable airbag that incorporates a fall-detection system that uses both acceleration and angular velocity signals to trigger inflation of the airbag. The fall-detection algorithm was devised using a thresholding technique with an accelerometer and gyro sensor. Sixteen subjects mimicked falls, and their acceleration waveforms were monitored. Then, we developed a fall-detection algorithm that could detect signals 300 ms before the fall. This signal was used as a trigger to inflate the airbag to a capacity of 2.4 L. Although the proposed system can help to prevent fall-related injuries, further development is needed to miniaturize the inflation system.**

***Index Terms*—Accelerometer, air bag, fall detection, fall prevention, gyro sensor.**

I. Introduction

FALLS are a serious problem for elderly people and others prone to falls. One-third to one-half of the population aged 65 years and over have experienced falls. Half of the elderly people who fall do so repeatedly. Falls are a complex phenomenon, suggesting present disease and predicting future disability. They are caused by interactions between the environment and dynamic balance, which is determined by the quality of sensory input, central processing, and motor responses. Falls are the leading cause of injury in older adults and the leading cause of accidental death in those over age 85 years.

Even a fall that does not result in injury can have serious consequences. Psychological trauma and fear of falling can produce a downward spiral of self-imposed reduced activity, leading to a loss of strength, flexibility, and mobility, thereby increasing the risk of future falls and injuries.

Fall-detection and prevention are important issues for the elderly population. The Hip Protect is the most popular device for preventing falls. From an engineering perspective, two main fall-detection technologies have been proposed: one uses motion sensors, such as accelerometers and gyro sensors [1]–[4], and the other uses image processing with a camera installed in the room [5], [6]. The thresholding technique is used to determine the direction and strength of a fall [3]. In addition, a gyroscope-based fall-detection sensor array can be used for image processing [4]. Another study installed a small digital video camera in the ceiling and classified falling patterns [5]. We sought to develop a means to reduce or prevent injuries associated with falls. Our method measures the acceleration before and during falls, and then inflates an airbag [7]. In a preliminary study, all falls were detected, but the airbag was activated occasionally during daily activities. Therefore, in this study, we developed a new fall-detection algorithm that uses both acceleration and angular velocity. Then, we tested a prototype airbag system.

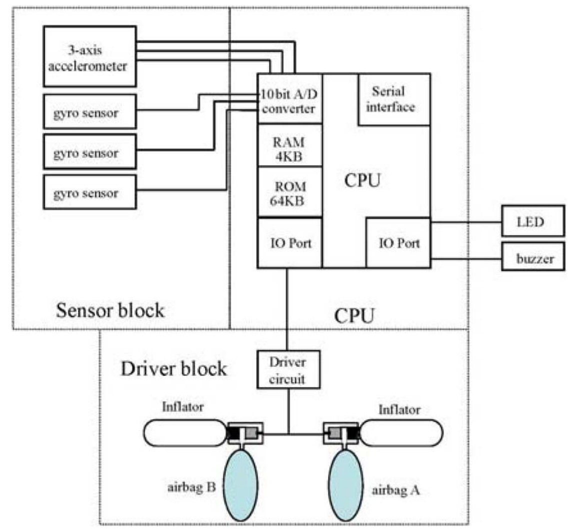

Fig. 1. Block diagram of the wearable airbag system.

II. Objects and Methods

A. Apparatus

The key issues regarding a wearable airbag are as follows.

1) It must be able to detect falls while the wearer is standing or walking.
2) It must protect the head and thighs.
3) It must be small, lightweight, and simple to wear.
4) It must be activated only during falls and not during daily activities.

Based on these considerations, our system consists of a wearable acceleration and angular velocity monitor and an airbag. Fig. 1 shows a block diagram of the device.

To monitor the acceleration and angular velocity, we designed a system with low power consumption, and then evaluated its battery life. The system must be small, light, and able to be worn without discomfort.

To evaluate the movement of the subject, the wearable system includes an accelerometer, a gyro sensor that measures the angular velocity of movement, and a CPU. The monitor measures $50 \times 56 \times 18$ mm and weighs 50 g. The system was designed

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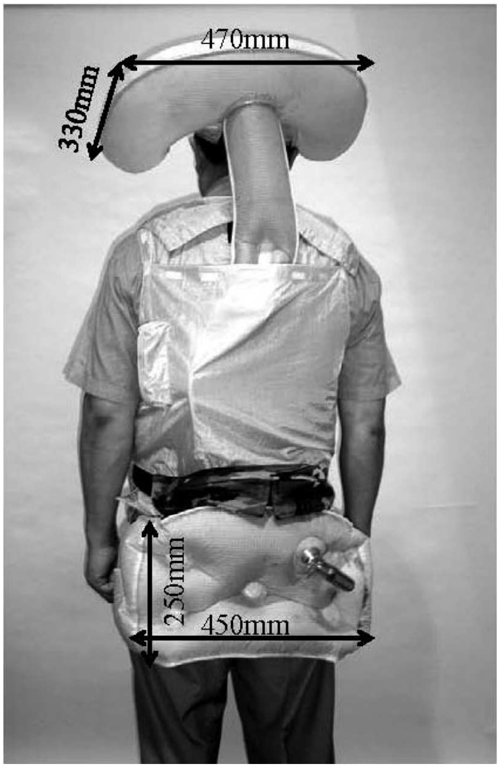

Fig. 2. Airbag system.

to operate without any complex setting. A triaxial acceleration sensor and a triaxial gyro sensor (Gyrocube 3A Oni-23503, O-NAVI, USA) were used to measure the subject's movement. The acceleration and angular velocity waveforms were converted into digital data with 16-bit resolution. The received data were transferred to the CPU and then analyzed with the fall-detection algorithm.

The airbag system consists of an inflatable airbag, a battery, a gas cartridge, sensors to determine acceleration and angular velocity, a trigger mechanism to release the gas, and an inflator to inflate the gas. Airbags protect both the head and the hips shown in Fig. 2. Before inflation, one bag is folded on the back; this bag covers the head and neck after inflating. This airbag measures 470 $\times$ 330 mm and has a volume of about 10 L. The airbag protecting the hips is folded inside a pouch; this bag covers the hips and thighs when inflated. It measures 250 $\times$ 450 mm and has a volume of about 10 L. Each airbag has an independent inflator and cartridge. The two airbags weigh 1.1 kg and are worn like a jacket. When the user falls, the sensor detects this and sends the trigger signal to automatically release gas from the cartridge to inflate the airbag and protect the user. Gunpowder is used to release the gas. When the triggering signal is generated, a 3-V signal is transmitted to cause ignition. Then, the gunpowder explodes, making a small hole in the gas cartridge. The inflator is made from an aluminum block big enough to avoid accidents when the gunpowder explodes. Each gas cartridge weighs about 160 g and measures 125 $\times$ 25 mm. The gunpowder weighs 100 mg. Our invention is superior to available devices because of its automatic deployment, compact size, light weight, ease of use, and reusability.

The system operates for about 200 h with an A3 alkaline battery. The operating switch is built into a belt, and a magnetic switch inside the buckle works when the buckle is closed.

B. Fall-Detection Algorithm

The main assumption in the fall-detection algorithm is that the wearer is in free fall. The acceleration signal during the fall is similar to one that occurs during free fall, i.e., the acceleration is zero. Considering human posture, the position of the senor, and the SNR of a low acceleration value, we assumed that a prevention acceleration value would be below ± 3 m/s^2. In addition, after a preliminary study of angular velocity, we added the stipulation that an angular velocity of less than 0.52 rad/s did not indicate a fall. Therefore, a fall occurred when the acceleration was less than ± 3 m/s^2 and the angular velocity exceeded 0.52 rad/s.

C. Experimental Setup

1) Verification of the Algorithm: The prototype system was tested by 16 young, healthy subjects (mean age 22.2 $\pm$ 5.1 years, weight 57.1 $\pm$ 8.0 kg, and height 167.8 $\pm$ 5.9 cm) who mimicked falls to the front, back, and sides while wearing the device without airbags. To prevent injuries, the subjects fell on a double mattress. In addition, we evaluated the effectiveness of the algorithm during daily life in an experiment performed by nine physiotherapists (mean age 31.2 $\pm$ 8.6 years, weight 56.0 $\pm$ 8.9 kg, and height 166.5 $\pm$ 9.4 cm) while walking, sitting down on a chair, getting out of bed, and lying down on a bed. The subjects wore the elderly simulator (Senior Pose, Daiwa House, Japan), which tightens a belt so that the wearer mimics the gait of an elderly person.

This trial was approved by the ethics committee of the Graduate School of Engineering, Chiba University. Written informed consent was obtained from each subject.

2) Experiment With the Prototype Device: We connected the monitoring system and airbag to four subjects, who performed a simple backward fall (mean age 23.0 $\pm$ 1.4 years, weight 63.3 $\pm$ 8.5 kg, height 173.5 $\pm$ 4.8 cm) to see whether the airbag inflated. The fall was monitored using a high-speed camera (exilim Ex-F1, Casio, Japan) at 300 fps. The airbag inflation time and fall time were measured from the images

III. RESULTS

A. Verification of the Algorithm

Fig. 3 shows typical examples of the acceleration and angular velocity signals during falls. Fig. 3(a) and (b) shows the acceleration and angular velocity, respectively, during backward falls. In Fig. 3(a), the vertical acceleration of the subject while standing was 9.8 m/s^2 (i.e., gravity). After 1.8 s, the large amplitude was the impact acceleration, corresponding to a fall. At 1 s after the start, the acceleration was decreased and approached zero. The arrow in this figure shows when our criterion (below ± 3 m/s^2) determined that a fall was occurring. Fig. 3(b) shows that swing increases the pitch direction of the angular velocity during a forward fall. The pitch signal starts to change 0.5 s

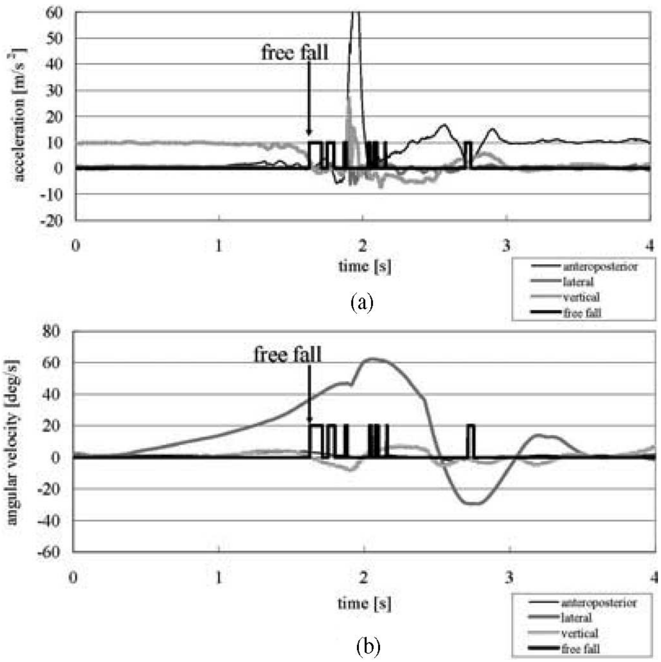

Fig. 3. Typical example of (a) acceleration and (b) angular velocity waveforms while mimicking a forward fall.

before the change in the acceleration signal, and the pitch angular velocity reaches a maximum value of 0.7 rad (40°)/s at the fall-detection time of 1 s.

We determined that an acceleration below ± 3 m/s^2 indicated free-fall conditions and that the angular velocity exceeded 0.52 rad (30°)/s while falling.

Table I shows the time of fall detection. From this, free-fall conditions were detected at an average of 193.4 $\pm$ 57 ms in forward falls and 197.4 $\pm$ 54.7 ms in backward falls, although 2 out of 51 forward falls and 5 out of 51 backward falls were not detected using these criteria.

Fig. 4 shows a typical example of a subject walking while wearing the elderly simulator. The vertical acceleration was less than 9.8 m/s^2 because of the forward posture in the elderly. The acceleration was less than ± 3 m/s^2 15 s, as shown with the arrow, but the angular velocity was around 0.52 $\pm$ 0.35 rad/s, so that errors were avoided.

B. Experiment With the Prototype Device

Fig. 5 shows the inflation of the airbag during a fall. Table II shows the timing of airbag inflation. The average of inflation time was 0.12 s. Fig. 5 shows that the airbag was inflated completely before the fall ended.

IV. Discussion

We determined that a fall occurred when the triaxial acceleration was below ± 3 m/s^2 and the angular velocity exceeded 0.52 rad/s. The key issues in fall injury prevention are the time it takes for the airbag to inflate and incorrect inflation caused by the algorithm.

TABLE I
Fall-Detection Time While Mimicking a Fall Using the Proposed Algorithm

Subjects	forward	backward	Subjects	forward	backward
	281	149		174	241
A	264	132	I	201	173
	299	140		188	155
	NA	186		165	176
B	184	206	J	171	187
	145	183		151	192
	137	111		187	177
C	NA	134	K	191	224
	166	132		187	192
	284	297		383	228
D	173	225	L	366	234
	216	191		276	181
	175	261		221	203
E	183	255	M	180	NA
	229	NA		198	NA
	208	369		128	212
F	145	281	N	136	140
	122	274		223	162
	169	237		166	181
G	162	248	O	179	128
	173	246		208	NA
	137	198		185	186
H	177	277	P	224	165
	210	219		210	169
				146	109
			Q	113	116
				126	NA
			Average	194.3	197.4
			SD	57.0	54.7

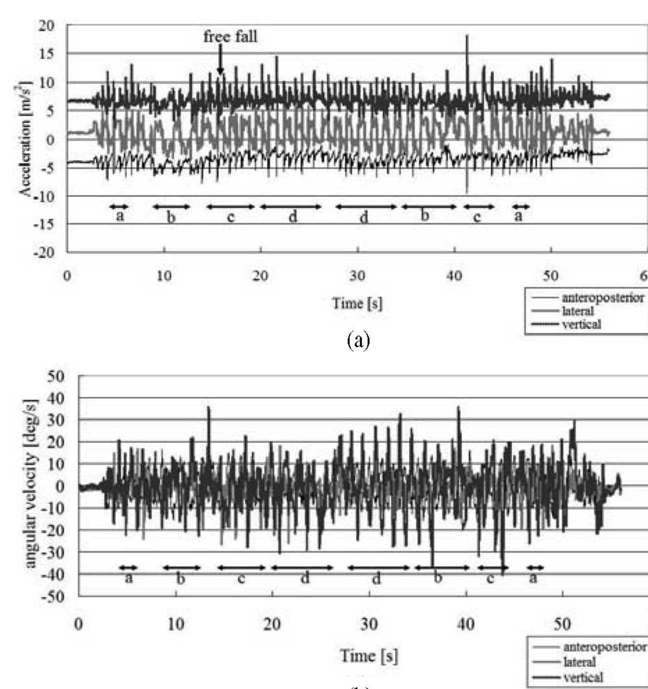

Fig. 4. Typical examples of (a) acceleration and (b) angular velocity waveforms while walking.

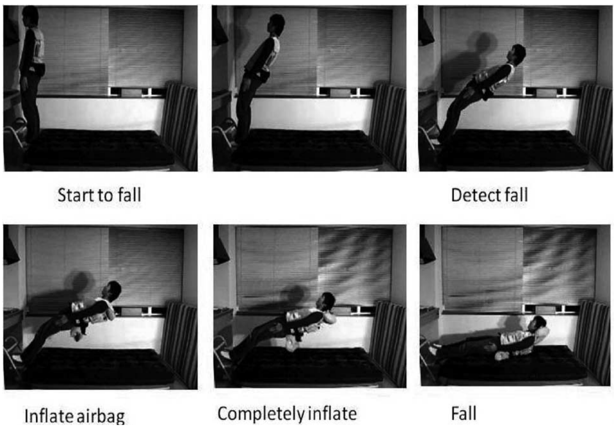

Fig. 5. Operation of the airbag system.

TABLE II
INFLATION TIME OF THE AIRBAG WHILE MIMICKING A FALL USING THE PROPOSED ALGORITHM

Subjects	Inflation time	Fall time
1	0.100	0.207
2	0.140	0.387
3	0.133	0.223
4	0.121	0.177
Ave	0.121	0.249
SE	0.019	0.094

During falls, the shortest and longest times before large impact acceleration were 111 and 378 ms, respectively. The airbag was inflated within this time interval. We successfully used an electromagnetic value in a previous study and a simulation study [7, Fig. 2]. However, in a real situation, the response of the electromagnetic value is insufficient. The previous study also suggested that the inflation time had to be less than 0.3 s to ensure that the airbag is deployed before a human falls to the ground [8], [9]. For inflation, we used a small amount of gunpowder, which is also used in automobile airbags. Further study is needed to improve the response of the electromagnetic valve.

Any fall-detection system must be very reliable. Our proposed algorithm had an accuracy of 93%. Errors occurred when the free-fall condition appeared before the angular velocity exceeded 0.52 rad/s. This resulted from a discrepancy in the detection times for acceleration and angular velocity. In these cases, the subject responded to the fall in a defensive manner by bending his/her knee and falling on the knee. Consequently, the body turned less, and the angular velocity was lower. If the subject had not assumed a defensive posture, the angular velocity would have been large enough to detect.

Further, any algorithm must be able to discriminate between a real fall and similar acceleration signals resulting from events in daily life. We analyzed activities that resulted in signals of ± 3 m/s^2, and by this criterion, jumping and running were determined to be "falls." Although elderly people do not jump and run often, the algorithm needs to be refined to differentiate jumping and running from genuine falls.

V. CONCLUSION

We developed a jacket to protect the head and hips when a person falls by automatically inflating an airbag that absorbs the shock of the fall and reduces the impact on the human body. The heart of this life jacket is a sensor that detects falls. The key characteristics of this fall sensor are the new fall-sensing algorithm, which uses a triaxial, single-unit accelerometer and angular velocity sensor, the jacket's compact design, and its battery-powered operation, which make it readily portable. For a reusable airbag, we need to develop a sophisticated electromagnetic valve. The use of this fall sensor and an airbag-equipped life jacket may also save lives and reduce injuries from falls at construction sites and other locations

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