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ARTICLE

Various surfaces challenge gait characteristics of ambulatory patients with spinal cord injury

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Abstract

Study Design A cross-sectional study.

Objective To assess the influence of various surfaces on the gait characteristics of ambulatory participants with incomplete spinal cord injury (SCI) as compared to data from able-bodied participants.

Setting A tertiary rehabilitation center and communities.

Methods Seventy participants (35 ambulatory individuals with incomplete SCI and 35 able-bodied individuals with gender- and age-matched) were assessed for their spatiotemporal gait variables while walking over a 10-m walkway of different surfaces (including hard, artificial grass, soft, and pebble surfaces) at a self-selected and fastest speed. The findings were analyzed using the method of manual digitization. The data among the surfaces were compared using Kruskal–Wallis test and Mann–Whitney U test, with a level of statistical significance at $P < 0.05$.

Results Participants with incomplete SCI could safely walk over every surface without any adverse events. Their average stride length, cadence, and walking speed, but not percent step length symmetry, were significantly decreased while walking on the artificial grass, soft, and particularly pebble surfaces as compared to those found on a hard surface. These changes were found particularly in those with SCI, resulting in a walking speed decreased from 0.11 to 0.35 m/s, whereas the reduction of walking speed of able-bodied participants ranged from 0.04 to 0.20 m/s.

Conclusions The spatiotemporal characteristics of ambulatory participants with SCI were dramatically affected by the surfaces as compared to the data found in able-bodied participants. The findings have potential clinical implications for the incorporation of various surfaces to promote the functional outcomes and safety for ambulatory individuals with SCI.

Introduction

Current rehabilitation programs for patients with neurological conditions, including those with incomplete spinal cord injury (SCI), emphasize the importance of task-specific practice. With the aim of walking and safety improvement, patients are trained to walk on a hard, smooth and flat surface, with minimal distraction [1, 2]. Such training surface differs from that in real-life situations at home and in their communities, where individuals frequently walk on grass as well as various unstable and irregular surfaces such as sand and pebble areas. Consequently, the outcomes of rehabilitation practice may not be effectively transferred to actual situations [3]. Thus, most ambulatory patients with incomplete SCI can walk only within their houses, at short distances, with abnormal spatiotemporal characteristics and a high risk of falls (34–75%) [4, 5].

Many studies have applied various surfaces, e.g., irregular and unstable surfaces, to challenge several aspects relating to mobility such as balance ability, muscular activity, and energy expenditure of their participants [6–11]. However, the data were confined to able-bodied young

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adults, older individuals, and people with amputees, or patients with diabetes mellitus [7, 11, 12]. To the best of our knowledge, there is no evidence on the influence of surfaces on gait characteristics of ambulatory individuals with incomplete SCI. Therefore, this study compared spatio-temporal gait variables of ambulatory participants with incomplete SCI while walking over hard, grass, soft, and pebble surfaces as compared to the data found in able-bodied individuals. The findings have potential clinical implications for the incorporation of various surfaces to promote the functional outcomes and safety of ambulatory individuals with incomplete SCI.

Methods

Participants

Ambulatory individuals with SCI were cross-sectionally recruited from a tertiary rehabilitation center and several communities. The inclusion criteria were aged at least 18 years, with an incomplete SCI as determined using the criteria of the American Spinal Cord Injury Association impairment scale: AIS C or D, and Functional Independent Measure-Locomotion scores of 5–7 (i.e., an ability to walk independently for at least 15 m continuously) [13]. However, these individuals were excluded if they had any conditions that might affect their ambulatory ability, such as unstable conditions, musculoskeletal pain with an intensity of more than 5 on a 10-point numerical pain rating scale, joint deformity, obvious leg length discrepancy, and severe spasticity of the lower extremities (i.e., a score of more than 2 on the Modified Ashworth Scale) [14, 15]. Able-bodied volunteers, with sex- and age-matched (±5 years) with those of SCI, were also invited to participate in this study [14].

The sample size was calculated with set the confidence level at 95% (significant level =0.05), the power of test at 90%, the $Z_{\alpha/2}$ at 1.96, Z_{β} at 0.84 [14, 16], and using the data from a pilot study (5 participants/group). The findings indicated that the study required at least 35 participants in each group. All participants read and signed a written informed consent document that was approved by the Khon Kean University Ethics Committee for Human Research (HE591368) before taking part in the study.

Research materials

The study applied four surfaces, including a hard, artificial grass, soft, and artificial pebble surface with 10 m long and 1 m wide for each surface. Details of each surface are as follows (Fig. 1):

Hard walkway	A hard concrete, smooth, and flat surface (Fig. 1a)
Grass walkway	An artificial high-density grass surface, with a leaf length of 4 cm and texture similar to that of natural grass (Fig. 1b)
Soft walkway	A compressed, unstable 3-inch thickness sponge surface (Fig. 1c)
Pebble walkway	An irregular surface, which consisted of lightweight artificial pebbles made of rigid polyurethane foam (i.e., materials used in limb prosthesis) attached to a yoga mat (Fig. 1d)

This study used artificial surfaces to promote similarity and applicability of these surfaces in several clinical and community settings involved in this study. Prior to being used, the safety of each surface, together with its similarity to a real surface, was verified by 30 physiotherapists with more than 5-year clinical experience. Then they were primarily verified for their safety and clinical application in able-bodied and older populations [17, 18].

Research protocols

All eligible participants were interviewed for their demographics (i.e., age, sex, body-weight, and height). Participants with SCI were also interviewed and assessed for their SCI characteristics (i.e., cause, stage, severity, and level of injury), and walking ability (Functional Independent Measure-Locomotion scores). Then all of them walked over the four surfaces without shoes in a random order at a self-selected and fastest speed for three trials over each surface (Fig. 1), and their spatiotemporal gait characteristics were recorded [19, 20]. Participants were allowed to use their customary walking device and to rest between the trials, if required. They had to fasten a lightweight safety belt with an assessor always being on their side throughout the trials [19, 20].

Outcome measures

Participants were assessed for their spatiotemporal characteristics, including stride length, cadence, walking speed, and percent step length symmetry using a camera-based motion capture (Nikon D5300 with a 60-Hz frame rate) while they walked over each surface. The camera was mounted at a position 3.5 m from the walkway to capture data over 4 m in the middle of the walkway (rhythmic phase). Prior to data recording, the system was calibrated using a known length object. The data were then analyzed using the method of manual digitization, which had excellent inter- and intra-rater reliability (0.98–0.99) and was

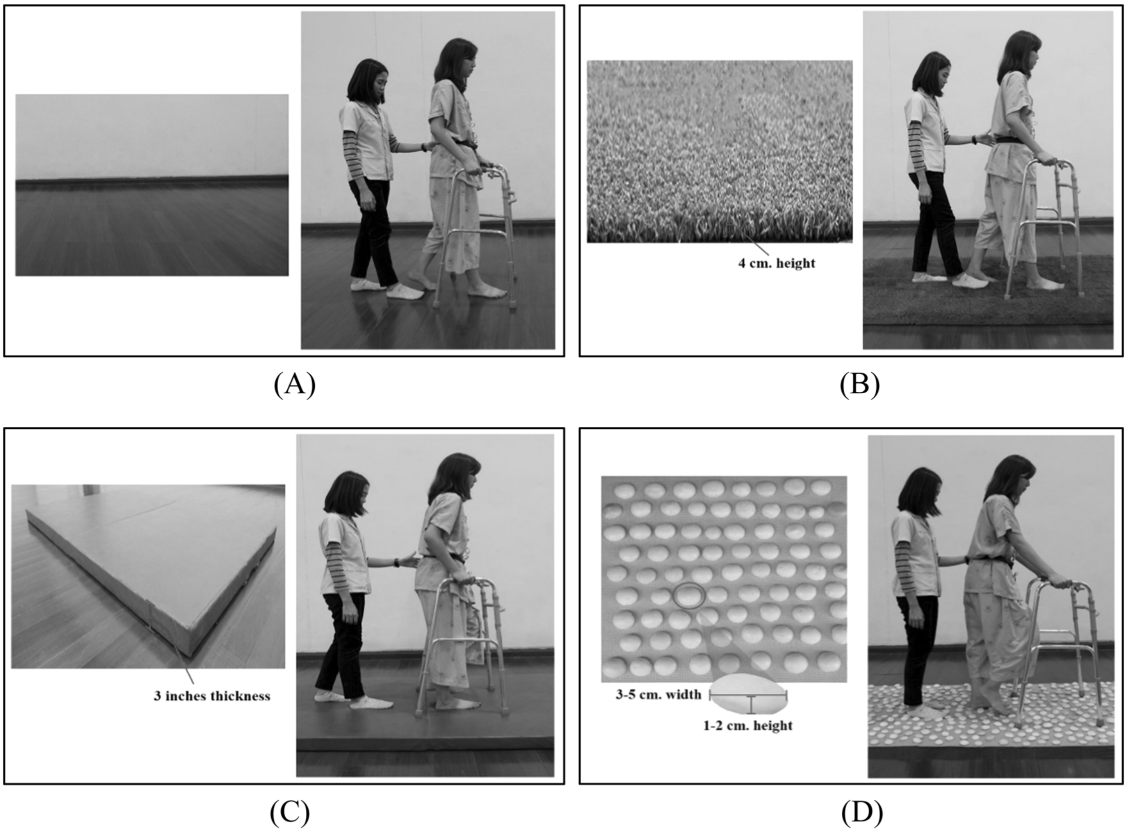

Fig. 1 Characteristics of the surfaces used in the study. **a** A hard, smooth and flat surface. **b** An artificial grass surface with a leaf length of 4 cm. **c** A soft surface (3-inch thickness compressed sponge). **d** An artificial pebble surface

practical in clinical and community settings [17, 21]. Details of the outcome analyses are as follows [14, 17, 21–23]:

Step length	Horizontal pixels between the heel of one foot and the heel of the other foot and scaling with respect to the calibration object (meters)
Stride length	The sum of average right and left step lengths (meters)
Cadence	The number of steps in 1 min (steps/minute)
Walking speed	Calculated using the formula: $\frac{\text{stride length} \times \text{cadence}}{120}$ (m/s)
Percent step length symmetry	Calculated using the formula: $\frac{\text{average data of the shorter step length}}{\text{average data of the longer step length}} \times 100$

The ideal percent step length symmetry is 93–100% [22].

Statistical analysis

Descriptive statistics were applied to explain the demographics of the participants and findings of the study. The gait characteristics while walking over the four surfaces were compared using the Kruskal–Wallis test. Then the Mann–Whitney U test was used to analyze the pairwise comparisons. The level of statistical significance was set at $P < 0.05$.

Results

Participants

Seventy participants completed the study (35 able-bodied individuals and 35 participants with incomplete SCI; Table 1). Most participants with incomplete SCI were at a chronic stage (average post-injury time more than 3 years), had mild lesion severity (AIS D), and usually walked with a walking device (Table 1). Their sensorimotor scores are presented in Table 2.

Spatiotemporal gait characteristics of the participants

The participants were able to walk on every surface safely without any adverse events, both at their preferred and

Table 1 Demographics and spinal cord injury (SCI) characteristics of participants

Variable	Able-bodied participants ($n = 35$)	SCI participants ($n = 35$)
Age (years), mean (SD)	54.9 (13.1) (50.4–59.4)	50.2 (13.7) (46.1–55.4)
Gender: male[a], *n* (%)	20 (57)	27 (77)
Body mass Index (kg/m^2), mean (SD)	23.7 (4.4) (22.2–25.2)	22.8 (3.3) (21.7–24.0)
Post-injury time (months)[a], mean (SD)		45.7 ± 39.3 (32.2–59.2)
Cause: traumatic SCI[a], *n* (%)		20 (57)
Stage of injury: chronic[a], *n* (%)		33 (94)
Severity of injury: AIS D[a], *n* (%)		25 (71)
Level of injury: incomplete paraplegia[a], *n* (%)		23 (66)
Functional Independence Measure-Locomotor Scores (FIM-L), *n* (%)		
FIM-L-5		1 (3)
FIM-L-6		20 (57)
FIM-L-7		14 (40)
Using a walking device, *n* (%)		
Yes		
Walker		12 (34)
Crutches		4 (12)
Cane		5 (14)
No		14 (40)

n number, *SD* standard deviation, *AIS* American Spinal Cord Injury Association Impairment Scale

Table 2 Sensorimotor scores of participants with incomplete spinal cord injury (SCI)

Variable[a]	All participants ($n = 35$)	Device users ($n = 21$)	Non-device users ($n = 14$)
UEs motor scores	45.7 ± 6.7	44.4 ± 6.9	47.7 ± 6.1
(total scores = 50)	(43.4–48.0)	(41.23–47.53)	(44.2–51.3)
Motor LEs	34.2 ± 10.1	28.7 ± 8.5	42.5 ± 5.9
(50 score total)	(30.6–37.7)	(24.8–32.6)	(39.1–45.9)
Light touch	96.9 ± 11.2	93.4 ± 12.6	102.2 ± 6.0
(112 scores total)	(93.1–100.8)	(87.7–99.2)	(98.8–105.7)
Pin prick	99.6 ± 9.5	96.7 ± 10.4	103.9 ± 6.1
(112 scores total)	(96.3–102.9)	(92.0–101.5)	(100.4–107.4)

LEs lower extremities, *UEs* upper extremities

Note: The data are presented using mean ± standard deviation (95% confidence intervals)

[a]The data were assessed as per the International Standards for the Neurological Classification of SCI

Device users refer to participants who daily walked with a walking device, and non-device users refer to participants who did not required any walking device

fastest speed. Their average stride length and cadence decreased significantly while walking on an artificial grass, soft, and particularly pebble surface, as compared with those when walking on a hard surface (Fig. 2). This reduction resulted in the decrement of walking speed ranged from 0.11 to 0.35 m/s (median = 0.66 (0.41: 0.91), 0.55 (0.33: 0.68), 0.48 (0.31: 0.60), 0.31 (0.24: 0.53) m/s for hard, grass, soft, and pebble surfaces) for participants with incomplete SCI, and from 0.04 to 0.20 m/s (median = 1.1 (0.17: 1.1), 1.0 (0.88: 1.1), 0.92 (0.82: 0.92), 0.85 (0.62: 0.94) m/s for able-bodied participants while walking on each surface, respectively (Fig. 2). The dramatic changes in incomplete SCI were found irrespective of whether they walked with or without a walking device (Fig. 3). Nonetheless, percent step length symmetry of the participants showed no significant differences among the surfaces

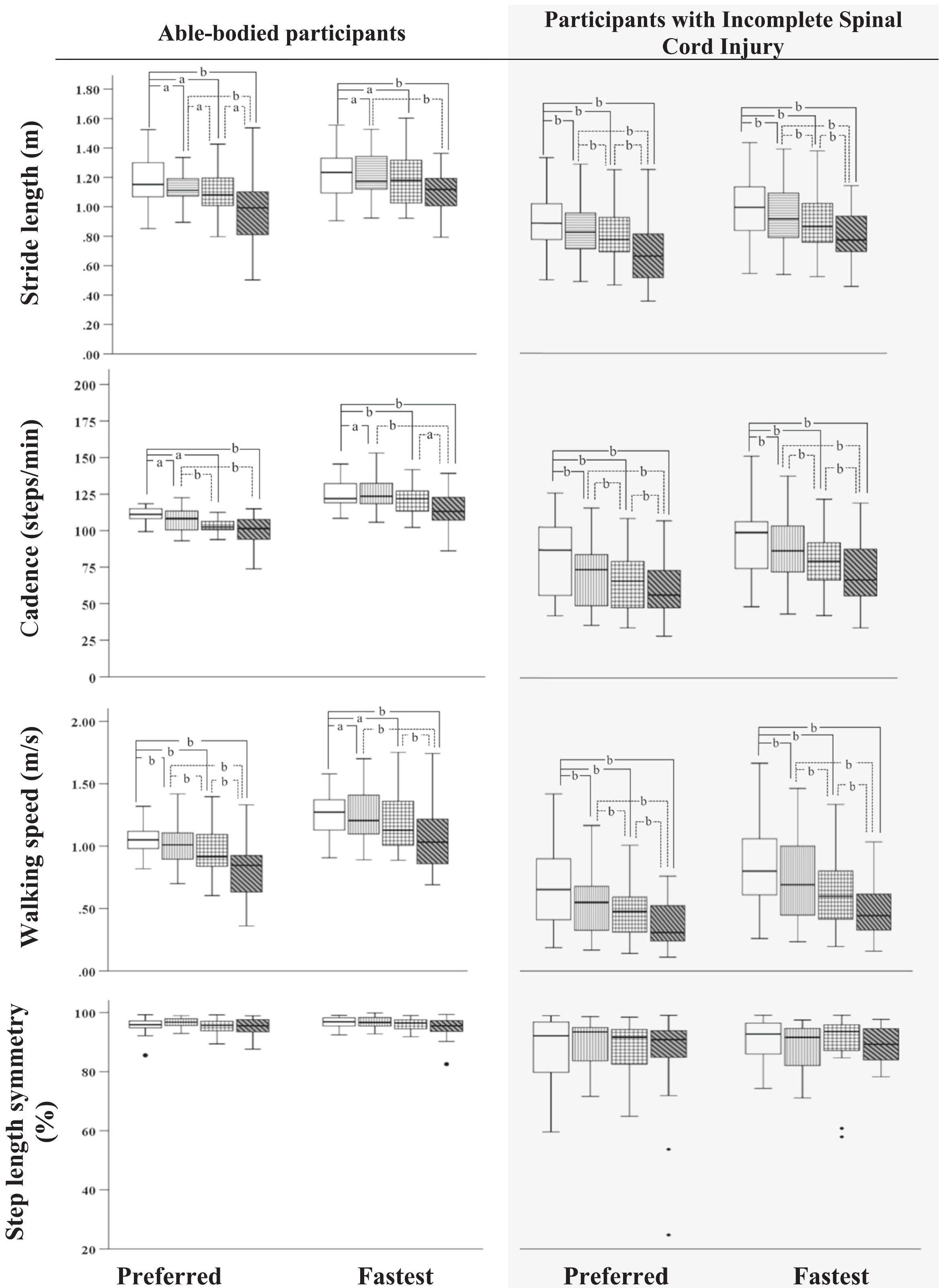

Fig. 2 Spatiotemporal characteristics of participants while walking on various surfaces at a preferred and fastest walking speed; [a]Indicate significant difference at $p < 0.05$, $^{b}p < 0.001$

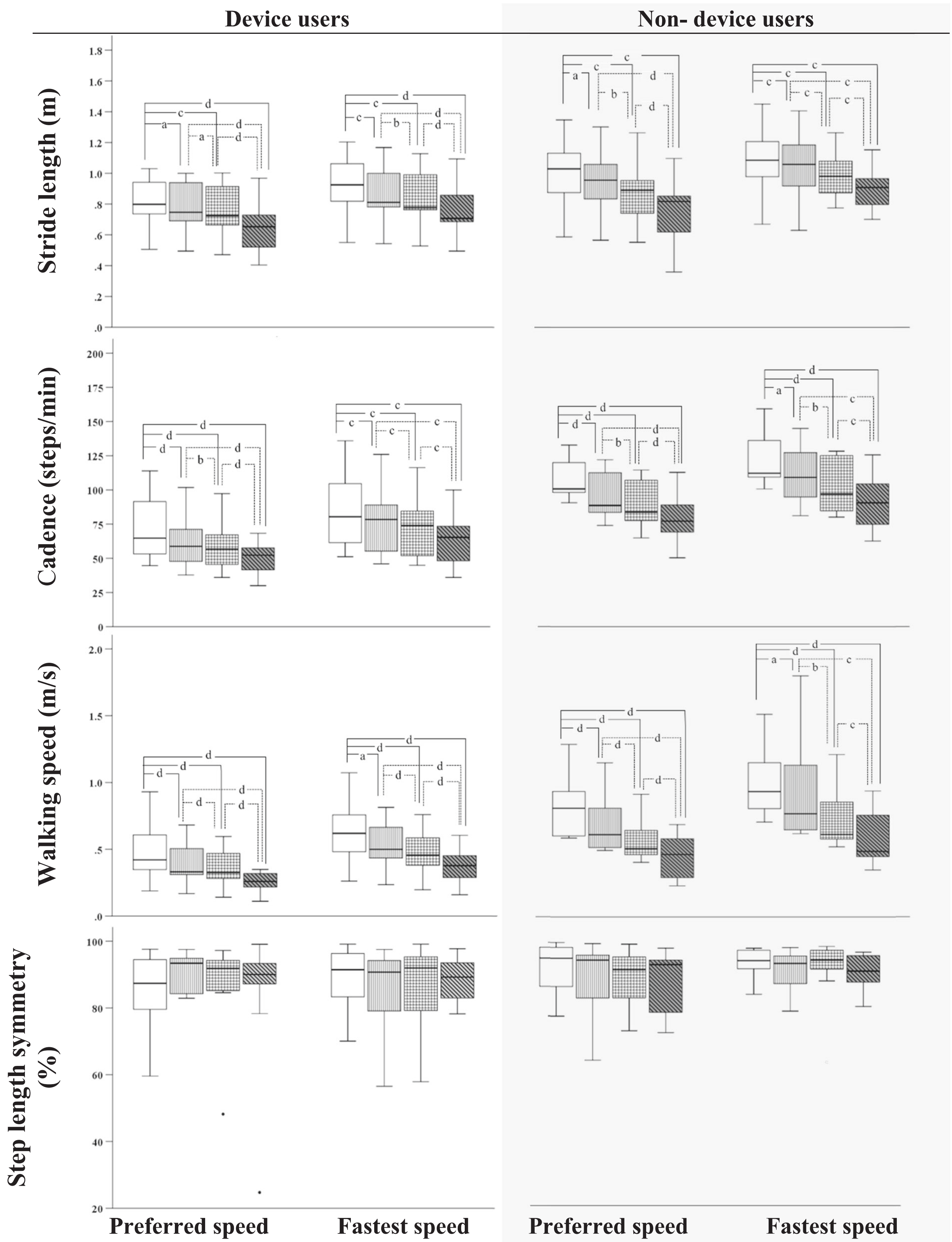

Fig. 3 Spatiotemporal characteristics of participants with incomplete spinal cord injury who walked with (device users) and without (non-device users) a walking device while walking on various surfaces at a preferred and fastest walking speed; [a]Indicate significant difference at p-value <0.05, [b]p-value <0.01, [c]p-value <0.005, [d]p-value <0.001

(Figs. 2 and 3), either when they walked at their preferred or fastest speed.

Discussion

Current rehabilitation therapy commonly takes place on a smooth and flat area of a rehabilitation room, which is different from the surfaces that individuals usually encounter in their daily living. The present study assessed the challenging effects of different surfaces, including a hard, artificial grass, soft, and artificial pebble surface, on spatiotemporal gait characteristics of ambulatory individuals with incomplete SCI and able-bodied individuals. The findings indicated that the participants could walk on every surface safely without any adverse events, but their spatiotemporal characteristics, except step symmetry, were dramatically affected by the surfaces used in the study.

The findings reflect the challenging effects of the surfaces on the walking abilities of the participants. Walking on the artificial grass surface attributed information through the leaf length that facilitated the participants to increase flexor strategy and toe clearance during a swing phase [6, 12]. Previous studies reported that the soft nature of grass also reduces the ground reaction force, thereby enhancing muscle activity and reducing the acceleration force during a swing period [6, 24]. Thus, the participants decreased their stride length, cadence, and walking speed while walking on a grass surface as compared with these parameters on a hard surface (Figs. 2 and 3). Similarly, a soft surface (3-inch thickness compressed sponge) reduces the mechanical work of the muscles and stability, while challenging balance ability, particularly during a single support period. It also clearly decreases the ground reaction force during a push-off phase. Thus, muscle activity, muscle co-contraction, and the requirements for balance control while walking on a soft surface increased as compared with these parameters when walking on a hard and firm surface [6, 25]. As a result, the participants also decreased their stride length, cadence, and walking speed while walking over a soft surface (Fig. 2).

Among these surfaces, the particular changes were found while the participants walked on an irregular, pebble surface. These changes may reflect the challenging effects of the surface during both stance and swing periods. During a stance period, the irregular pebble surface increased demands on balance control and muscle activity [9, 12, 26]. During a swing phase, the irregular pebble surface also required the participants to increase the toe clearance to enable successful walking over various sized pebbles [9, 27]. Previous studies also reported that an unstable and irregular surface increases proprioceptive demands and challenged balance control ability [9, 10, 26]. Such demanding surfaces obviously affected walking ability of the participants, especially during a single support phase. Therefore, they reduced their step length and cadence in order to minimize the duration of a single limb support period or the task demands, and the risk of injury while walking over such areas (Figs. 2 and 3) [8, 11]. These movement modifications further affected walking speed of the participants, thus they walked dramatically slower than that on a hard surface. However, these challenging effects were attributed to both lower limbs of participants with bilateral intact (able-bodied individuals) and impaired (participants with SCI) sensorimotor functions, hence the proportion of percent step length symmetry showed no clear differences among the surfaces (Fig. 3).

The influence of these surfaces was demonstrated particularly in ambulatory individuals with SCI in which their walking speed decreased from 0.11 to 0.35 m/s while walking on each surface (Figs. 2 and 3). These changes are clinically meaningful [28] and reflect the consequences of sensorimotor deteriorations following SCI (Table 2) that reduced their self-confidence and ability of movement modification according to the task demands. Although the sensorimotor deficits were particularly evidenced in participants who walked with a walking device (Table 2), the upper limb contribution (via a walking device) might help to compensate for these deficits while walking over challenging areas. Therefore, the effects of these surfaces on the ambulatory abilities of participants with incomplete SCI were similar, irrespective of whether they used a walking device (Fig. 3).

The present findings confirm the safety issues and the challenging effects posed by various surfaces that are commonly encountered in daily living. Thus the inclusion of such surfaces in rehabilitation programs may help to promote functional ability and levels of independence, in addition to minimizing the risk of falls of ambulatory individuals with incomplete SCI. However, some limitations need to be addressed for data interpretation. This study used surfaces from artificial materials (e.g., grass, sponge, and pebbles) to simulate ambulatory environments encountered in daily living such as grass, sand, and pebble areas, and promote the similarity of the surface used for various clinical and community settings involved in this study. Prior to their use, the suitability of these surfaces and their similarity to real surfaces were confirmed by 30 experienced physiotherapists, able-bodied, and older populations [17, 18]. Although repetitive walking on such areas may increase learning effects on the subsequent trials, the sequences of these surfaces were randomly assessed in order to keep the learning effects at a minimum. Moreover, the study excluded individuals with SCI who had severe spasticity of the lower extremities (i.e., a score of >2 on the Modified Ashworth Scale) because they may have limit walking ability and high risk of fall during walking. The researchers believed that such patients may be better trained to walk over a smooth and flat area to promote their self-confidence while practicing walking. Therefore, the findings preliminary confirm the incorporation of various surfaces in clinical rehabilitation for ambulatory individuals with SCI who have rather good walking ability (FIM-L scores = 5–7), and do not have severe spasticity. However, a further investigation using real surfaces, in individuals with severe spasticity and rather low walking ability, with the measurement of other variables, e.g., ground reaction force, muscle activities, and self-confidence, is needed to extend the benefit of these surfaces for ambulatory individuals with SCI.

Data archiving

All reasonable requests for participant-level data upon which the results of this study are based will be considered.

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Author contributions All authors were responsible for study conception and design, and drafting of manuscript. DP was also involved in data acquisition, statistical analysis, and data interpretation. SA was additionally responsible on project management, funding application, data interpretation, and finalized the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical statement We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during this research.

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