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AAP-4275; No. of Pages 7

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Accident Analysis and Prevention xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

SOFIE, a bicycle that supports older cyclists?

R. Dubbeldam[a,*], C. Baten[a,b], J.H. Buurke[a,b], J.S. Rietman[a,c]

[a] Roessingh Research & Development Roessinghsbleekweg 33, 7522 AH, Enschede, The Netherlands
[b] Department of Biomedical Signals and Systems, University of Twente, PO box 217, 7500 AE, Enschede, The Netherlands
[c] Department of Biomechanical Engineering, University of Twente, PO box 217, 7500 AE, Enschede, The Netherlands

ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form 22 July 2016
Accepted 6 September 2016
Available online xxx

Keywords:
Cycling kinematics
Older cyclists
Cycling safety
Mounting and dismounting

ABSTRACT

Older cyclists remain at high risk of sustaining an injury after a fall with their bicycle. A growing awareness for the need and possibilities to support safety of older cyclists has been leading to bicycle design ideas. However, the effectiveness and acceptance of such designs has not been studied yet. This study aims to analyse the effect of 3 support systems: an automatic adjustable saddle height, optimised frame and wheel geometry and drive-off assistance. The support systems are integrated on the SOFIE bicycle, a prototype bicycle designed to support older cyclists during (dis-)mounting and at lower cycling speeds.

Nine older cyclists (65–80 years) were asked to cycle on a 'normal' and on the 'SOFIE' bicycle. They cycled on a parking lot to avoid interaction with traffic. The following tasks were analysed: cycling at comfortable and low speed avoiding an obstacle and (dis-)mounting the bicycle. Bicycle and cyclist motions were recorded with 10 Inertial Measurement Units and by 2 video cameras. FUSION software (LABVIEW) was used to assess kinematic parameters. First, a subjective analysis of the different cycling tasks was made, supported by video analysis. Second, differences in cyclist and bicycle kinematic parameters between the normal and SOFIE bicycle were studied for the various cycling tasks.

The SOFIE bicycle was experienced as a 'supportive' and comfortable bicycle and objectively performed 'safer' on various cycling tasks. For example: The optimised frame geometry with low step-in enabled a faster (dis-)mounting time and less sternum roll angle and angular acceleration. The adjustable saddle height enabled the participants to keep both feet on the ground till they started cycling with the 'drive-off' support. The latter reduces steering activity: maximum steer angle and angular acceleration. During sudden obstacle avoidance, less upper body and thigh accelerations are recorded. In conclusion, the SOFIE bicycle was able to support older cyclists during various cycling tasks and may reduce fall risk.

1. Introduction

While the fatal and serious injuries from car accidents are reducing as a consequence of safety measures, the number of fatal and serious injuries from bicycle accidents remains constant (Wijlhuizen et al., 2012). Depending on country, 35–70% of the fatal and severe bicycle accidents are caused by motor vehicle-bicycle crashes (Eilert-Petersson and Schelp, 1997; Niska et al., 2013; Richter et al., 2007; Siman-Tov et al., 2012; Van kampen, 2007). On the other hand, about 5–30% of the fatal cyclist injuries are caused by a single bicycle accident, an accident in which no other road user is directly involved. Furthermore, 60–95% of cyclists admitted to emergency departments are victims of single bicycle accident (Schepers et al., 2014). In the Netherlands for example, each year 12000 older cyclists are more or less severely injured as consequence of such a single bicycle accident, and this number is increasing (Consumer Safety Institute, 2010). Also the risk of sustaining an injury after a single bicycle accident increases with age, from 55 years and older, the risk of injury increases with a factor 2 at 70 years and up to factor 4 to 8 for 80 year old males and females respectively (Consumer Safety Institute, 2010)

Several (in-depth) accident analysis studies have determined the cause and the critical situations of single bicycle crashes (Niska et al., 2013; Kruijer et al., 2013; Panneman and Klein Wolt 2015,,2012; Hagemeister and Tegen-Klebingat, 2013; Reynolds et al., 2009; Scheiman et al., 2010). Single-bicycle accident causes may be infrastructure related such as bad and slippery roads, cyclist related such as distraction and inappropriate behaviour, or bicycle related such as failing brakes. Older cyclists more often report the single-bicycle accident to be consequence of their own behaviour (40%) than younger cyclists (30%) (Panneman and Klein

* Corresponding author.
E-mail addresses: r.dubbeldam@rrd.nl (R. Dubbeldam), c.baten@rrd.nl (C. Baten), j.buurke@rrd.nl (J.H. Buurke), j.s.rietman@rrd.nl (J.S. Rietman).

http://dx.doi.org/10.1016/j.aap.2016.09.006
0001-4575/

Wolt, 2015). The bicycle as such is blamed in 5–20% of the cases. So far, infrastructural improvements as well as road user behaviour have been the main focus to improve safety of older cyclists (Twisk et al., 2013; Reynolds et al., 2009; Schepers, 2008). However, from the age of 55 years, older cyclists still remain at high risk of sustaining an injury after a fall with their bicycle (Kruijer et al., 2013; Niska et al., 2013).

The critical accident situations include among others (dis)mounting, braking, turning left or right and obstacle avoidance. For the older cyclists, 22% of the falls occurred during (dis)mounting compared to 8% for the younger adults (Panneman and Klein Wolt, 2015). Reasons given for the fall were among others saddle height and a vertical incline of the road. (Davidse, 2014; Schepers and Klein-Wolt, 2014). Schepers and Klein-Wolt discussed physical weakness may be the cause for higher fall risk during (dis)mounting for older cyclists (Schepers and Klein-Wolt, 2012). Dubbeldam et al. demonstrated that older and younger adults use different (dis)mounting techniques: older adults often use a stepping technique, which may be a more risk full technique since higher thigh accelerations were measured for older cyclists compared to younger (Dubbeldam et al., 2016). On the other hand, this technique enabled the older cyclists to reach a cycling speed of at least 5 km/h more quickly compared to the young cyclist mounting technique. Since slow cycling speeds require more balancing actions (Moore et al., 2011), another reason for the many falls during (dis)mounting may be the difficulty older cyclists have with maintaining balance at low speeds. Prior studies confirm the effect of age on for example increased steering during slow cycling (Bulsink et al., 2016; Dubbeldam et al., 2015). Also avoiding an obstacle (11%) and going up a steep (5%) more frequently leads to falls for older cyclists compared to younger adults (8% and 3% respectively). The slower reaction time of older cyclists may be of influence during obstacle avoidance (Collins et al., 1995; Lajoie and Gallagher, 2005; Salthouse, 2000). Fall risk during going up an incline may be explained by the required additional force and consequently slow cycling speed during such situations.

Simple bicycle modification are possible and may enhance safety for older cyclists. For example the possibility to remain with two feet on the floor during (dis)mounting provides a much more stable posture before cycling off or dismounting. A bicycle with features supporting balance or steering at slow speeds or features supporting the cyclist to reach a stable cycling speed quicker, may reduce fall risk during for example: the transition phases from (dis) mounting to cruising, looking behind and or other activities that take place at low cycling speeds. A growing awareness for the need and possibilities to support safety of older cyclists and avoid a fall has been leading to various bicycle design ideas. Several of these ideas aim to enhance balance of the bicycle and cyclist or support the cyclist in his or her limitations. However, not all ideas are acceptable for the older cyclists, as they experience them to be stigmatising; For example the tricycle or rear-view mirrors are not well accepted. The so-called SOFIE bicycle has been especially designed to enhance safety and comfort of older cyclists by means of three simple and readily available support systems, which include an automatic adjustable saddle height, optimised frame and wheel geometry and drive-off assistance. However, the effectiveness and perhaps even more important, the acceptance of such designs and corresponding willingness to use it, have not been studied yet.

There are no guidelines how to safely evaluate the safety performance of a bicycle in terms of procedure or measures. A retrospective analysis of occurring accidents may, on the long term, provide best information on safety performance. At present however, one would want to test and evaluate the safety enhancements in several critical situations related to fall risk, but in a safe environment. Many factors play a role regarding fall risk: the cyclist, the bicycle, the infrastructure and other road-users. Since this study focuses on bicycle design and its potential to enhance balance of the cyclist, the other factors will not be taken into account. As mentioned previously, several cycling situations have been related to fall risk and can be a start for enhanced balance product evaluation: mounting and dismounting, cycling at low cycling speeds and sudden avoidance of an obstacle.

Regarding measures, an objective evaluation of cyclist and bicycle balance may be given in terms of spatio-temporal and kinematic parameters. Modelling and treadmill studies have identified several mechanisms how the cyclist maintains balance on the bicycle: At cruising speed, steering of the handlebar is most important. When cycling speed reduces, the steering increases but also upper body and leg (lateral) motions increase. This becomes evident at cycling speeds below 5 km/h, where the lateral leg motion increases to maintain balance (Moore et al., 2011). In addition to objective measures, a subjective analysis is also required, since a product will not be bought or used if it has not been accepted by the end-user. Questionnaires on how older cyclists experience the bicycle in terms of stability and safety are not readily available. A visual analogue scale or a 5 point Likert scale can be used for such purposes. The User-acceptance scale has been used to evaluate driver assistance technologies in cars (Van der Laan et al., 1997). This scale can also be used for other vehicles and a wide scale of assistance technologies.

A representative safe test procedure consisting of various critical cycling situations and corresponding measures for analysis can be developed. Accordingly, the aim of this study was to register and analyse the performance of the SOFIE bicycle, a prototype, by means of such a test procedure. Performance was measured objectively by means of kinematics parameters and subjectively by means of an overall user-acceptance score.

2. Methods

2.1. Participants

Nine older cyclists were recruited to cycle on a 'normal' and on the 'SOFIE' bicycle. Recruitment took place via former contacts, and all participants signed an informed consent. This study was approved by the Medical Ethical Committee Twente, Enschede, The Netherlands. The inclusion criteria for the study were: age 65 years and older, regular cycling experience of at least twice a week and the ability to cycle 20 min without motor support. The exclusion criteria included: serious visual or auditory impairments and a history of bicycle falls resulting in serious injuries. We recorded the following demographic data: gender, age, body weight (to asses Body Mass Index), height, SF36 Health survey (Aaronson et al., 1998), self-reported medication usage and degenerative diseases.

2.2. Test protocol

The participants cycled on a parking lot to avoid interaction with traffic. First the participants cycled on the normal bicycle and subsequently on the SOFIE bicycle (Fig. 1). The following cycling tasks were performed and recorded twice on each bicycle: straight cycling at comfortable speed, straight cycling as slow as possible, cycling straight and avoiding an obstacle, and (dis-) mounting the bicycle. Cycling speed was self-chosen by the participants.

Before the tests, the participant was given time to familiarise himself with the two bicycles and adjust saddle height as required.

2.3. Measurement system

The normal bicycle was familiar to all: a female version of a typical Dutch design, the TREK L300 BLX low with 50 cm frame height. This bicycle has a relative low step-through at 40 cm (and 18 cm wide). Such a bicycle is used by male and female older cyclists

Fig. 1. The normal bicycle and the SOFIE bicycle from this study.

in the Netherlands. According to the frame geometry and average anthropometric data of leg and total body length, this bicycle is suitable for cyclists with a length between 155 and 185 cm. The SOFIE bicycle has been designed with recommendations from prior computer modelling and experimental cycling studies with older and young cyclists (Dubbeldam et al., 2014, 2015). The SOFIE bicycle is a prototype and has several support systems:

- An automatic adjustable saddle height: the saddle is able to automatically mount 7 cm. Initially the saddle is in low position. Only when the cyclists sits on the saddle and starts putting pressure on the pedal, the saddle moves up to its high position. Consequently, the participant is able to sit down on the saddle with both feet on the floor: a stable posture to start off cycling. At cruise speed, the saddle will be in high position and the cyclist is able to fully stretch his legs while pedalling (Fig. 2). The saddle automatically descends when the brakes are applied or when the cycling speed drops below 8 km/h. The low-saddle position can be adjusted between 870 mm and 990 mm height from the ground. This makes the bicycle suitable for cyclists with a body length between 168 and 189 cm.
- The bicycle frame and wheel geometry are optimised to be self-stable from a lower cycling velocity than bicycles with a typical Dutch frame design and larger wheel diameter. Self-stable means that the bicycle (without cyclist) remains upright after obtaining an initial push that accelerates the bicycle to a specific velocity (Kooijman et al., 2011). At lower or much higher velocities the bicycle will fall over. So it is expected that on the SOFIE bicycle, less balancing is required from the cyclist at low cycling velocities. Furthermore, the step-through is low (13 cm wide at minimum height of 26 cm, and 18 cm wide at 32 cm high), enabling easy access to the other side of the bicycle during (dis-)mounting.
- The electric motor with drive-off assistance offers fine-tuned, hardly noticeable but effective, power assistance from the moment the cyclist puts pressure on the pedals. The electric motor supports the cyclists up to 18 km/h.

The bicycle and cyclist motions were recorded with 10 Inertial Measurement Units (MTw-38A70G20 Xsens, Enschede, The Netherlands) and by 2 video cameras (HERO2, GoPro, Inc., USA). The FusionTools software (Roessingh Research and Development, Enschede, The Netherlands) was built around the Xsens sensor SDK MT 3.81 and was used to assess kinematic data of the 10 body segments (Baten et al., 2004). One sensor was attached to the bicycle frame and one to the handle bar to assess the bicycle kinematics. The other eight sensors were attached to the cyclist on the left foot, right foot, left shank, right shank, left thigh, right thigh, pelvis/sacrum and sternum (Fig. 2).

2.4. Analysis

A subjective analysis of the different cycling tasks was assessed through self-reported 'experiences' and 'feelings' while cycling on the different bicycles and for the different cycling tasks. On 5-point Likert scales the participants were asked to score for pleasantness, safety, risk, annoyance and stability (*Experience*) as well as confidence, fear, stability (*Feeling*). Each answer was rated from −2 to +2, with +2 representing a positive experience. The total score of the 8 individual questions was calculated for each cycling task as indication of how the cyclist experienced the bicycle in that particular situation (maximum score of 16 points). Then a total score for all four situations was calculated for each cyclist and bicycle. Furthermore, the user-acceptance of the SOFIE support technology was evaluated by means of the Van der Laan scale (Van der Laan et al., 1997). This questionnaire consists of 5 questions on "Usefulness" and 4 questions on "Satisfying". Each question is answered on a 5-point Likert scale, which was rated from −2 to +2. Hence, maximum positive attitude on user-acceptance is reflected by a maximum score of +18 points, a neutral attitude is reflected by 0 points. The video recordings were used to subjectively compare the steering amplitudes and sway across the road for the two bicycles in the different cycling tasks.

The cyclist and bicycle kinematic parameters between the normal and SOFIE bicycle were compared for the different cycling tasks. These parameters included minimum, maximum and or variability (in terms of standard deviation) of:

- Bicycle steer, roll and sway angle, angular velocity and angular acceleration
- Sternum roll, sway and pitch angle and angular acceleration, lateral acceleration
- Left and right thigh sway and pitch angle and angular acceleration

Where sway is the rotation angle around the vertical z-axis, roll is rotation around the cycling direction axis and pitch is rotation around the y-axis, perpendicular to x- and z-axis. Since standing on one leg is a balancing issue for many older cyclists, the time spent to lift the foot to other side of the frame onto the ground

Fig. 2. Getting used to mounting the SOFIE bicycle: stepping through frame, sit on saddle, put one foot on pedal and cycle off while saddle height is increasing.

Please cite this article in press as: Dubbeldam, R., et al., SOFIE, a bicycle that supports older cyclists? Accid. Anal. Prev. (2016), http://dx.doi.org/10.1016/j.aap.2016.09.006

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Table 1
Demographic characteristics. Group average (mean) and corresponding standard deviation (SD) values.

	Older cyclists (N = 9)
Gender	5 m/4 f
Age	72 (5) years
Height	174 (7) cm
BMI	25 (2) kg/m^2
SF-36	PCS 53 (4), MCS 54 (7)

Table 2
Cycling velocities at various tasks. Group average (mean) and corresponding standard deviation (SD) values.

	Normal bicycle	SOFIE bicycle
Comfortable cycling speed (m/s)	4.5 (0.4) m/s	4.7 (0.4) m/s
Slow cycling speed (m/s)	2.3 (0.6) m/s	2.5 (0.4) m/s
Obstacle avoidance speed (m/s)	3.7 (0.3) m/s	4.0 (0.6) m/s

(or onto the pedal) during (dis-)mounting was assessed. Descriptive analyses were performed and the mean and standard deviation (SD) values reported. By means of histograms the data distribution, parametric or non-parametric, was assessed. Then, non-parametric dependent T-tests (Wilcoxon signed-rank test) were used to study the differences between the two bicycles. All statistical analyses were performed in SPSS (Statistical Packages for Social Sciences, 20.0, SPSS Inc, Chicago, Illinois, USA).

3. Results

3.1. Participants

In this study, 5 males and 4 females with a mean age of 74 (SD 4) years participated and were able to perform all cycling tasks. The youngest participant was 68 years old and the oldest participant was 79 years old. The participants had a height of 174 (SD 7) cm and Body Mass Index of 25 (SD 2) kg/m^2. They were all in good physical and mental health according to the physical and mental component summary (PCS and MCS) of the SF-36. An overview of the demographic data is given in Table 1. The participants needed and were given time to get used to the SOFIE bicycle. Especially the way to mount and dismount the SOFIE bicycle was new, since it is not possible for most cyclists to keep both feet on the floor when sitting down on the saddle of their own bicycle. Therefore, a different (dis-)mounting strategy had to be learned for the SOFIE bicycle as can be observed in Fig. 2.

The older participants cycled at 16 to 17 km/h for comfortable straight cycling and at 8 to 9 km/h for slow straight cycling. The cycling speed for sudden obstacle avoidance could be chosen freely and depended on the courage or self-efficacy of the participant. An overview of the average cycling speeds for the various tasks is given in Table 2. No statistical significant differences were observed.

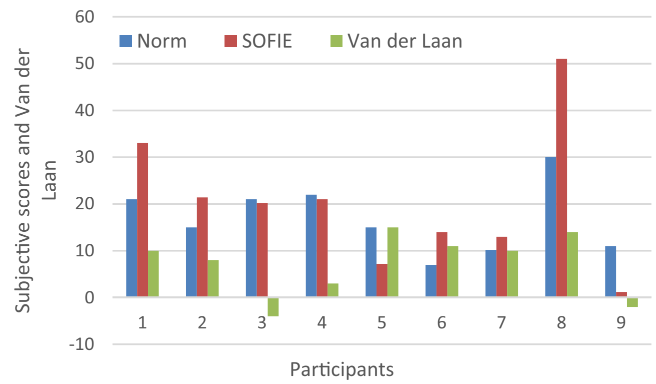

Fig. 4. Overview of total subjective score for normal (Norm) and SOFie (SOFIE) bicycle (maximum positive experience 4 × 16 = 64 points) and Van der Laan score for SOFIE user-acceptance (maximum negative acceptance −18, neutral 0, maximum positive acceptance +18 points) for each participant and bicycle.

3.2. Subjective analysis

There were no statistical significant differences for the total subjective 'experiences' and 'feeling' between the normal and SOFIE bicycle for mounting, dismounting, slow cycling and manoeuvring. However, 4 to 5 participants reported a more positive experience and feeling, i.e. higher values, on the SOFIE bicycle for dismounting and manoeuvring, respectively (Fig. 3). Zero points indicated neutral experience, while 16 points indicated maximum positive experience. The total subjective score for all cycling tasks together was not significantly different between normal bicycle and SOFIE bicycle with a group average of 18 (SD 8) and 22 (SD 14) points respectively.

The user-acceptance of the SOFIE bicycle was good with a mean Van der Laan score of 7.2 (SD 6.8, and statistically significantly different from zero (p 0.013)). Seven participants were positive about the SOFIE bicycle, as indicated by a value larger than zero (Fig. 4). Only two ladies scored a negative user-acceptance due to a negative sub-score for "Satisfying". In general, the subjective score for SOFIE and the user-acceptance score showed the same trend: a positive score on user-acceptance coincided with a higher (or similar) subjective experience score for the SOFIE bicycle compared to the normal bicycle.

3.3. Kinematic analysis

3.3.1. (Dis)Mounting

The time spent balancing on one leg, trying to get the other leg to the other side of the frame, is statistically significantly lower for the SOFIE bicycle for dismounting, compared to the normal bicycle: on average 2.0 (SD 0.5) seconds compared to 2.9 (SD 0.7) seconds, respectively. Also for mounting, the balancing time for SOFIE tended to be shorter than for the normal bicycle: on average 2.1

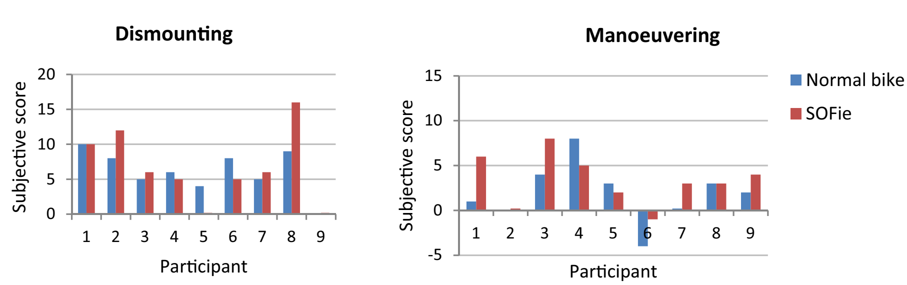

Fig. 3. The Individual participants (N = 9) subjective experiences for the normal bicycle and SOFIE bicycle for the two cycling tasks dismounting and manoeuvring. Experience is scored with 8 questions resulting in maximum negative experience −16 points and positive experience +16 points.

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Table 3
Overview kinematic parameters during the various cycling tasks. With acceleration (acc), degree (deg), second (s), maximum (max.), standard deviation (SD). * Statistical significant difference between bicycles for p < 0.05.

		Normal Bicycle		P-value	SOFIE bicycle	
		Mean	SD		Mean	SD
Mounting	Time spent on one leg (s)	2.4	0.7	0.07	2.1	0.6
	Max. steer angle (deg)	61.7	6.9	0.05*	47.2	18.0
	Max. sternum roll angle (deg)	20.1	6.2	0.03*	23.9	6.2
	Max. sternum roll acc. (deg/s^2)	1919	726	0.05*	1490	480
	Max. sternum pitch acc. (deg/s^2)	1552	926	0.03*	1198	507
Comfortable straight cycling	Left thigh sway SD (deg)	18.6	6.7	0.01*	10.2	3.9
	Right thigh sway SD (deg)	13.2	6.4	0.02*	9.7	5.8
	Bicycle roll SD (deg)	1.0	0.3	0.04*	1.3	0.5
	Max. left thigh sway (deg)	25.4	12.7	0.03*	13.1	12.8
	Max. right thigh sway (deg)	18.0	5.7	0.05*	13.0	5.9
	Max. steer angle (deg)	56.5	6.1	0.01*	18.8	30.3
	Max. steer acc. SD (deg/s^2)	104.8	34.1	0.01*	145.1	50.1
	Max. steer acc. (deg/s^2)	360	104	0.05*	600	431
Slow straight cycling	Left thigh SD (deg)	16.5	3.6	0.01*	9.1	4.0
	Right thigh SD (deg)	14.2	4.6	0.01*	7.2	4.8
	Max. left thigh sway (deg)	20.9	8.9	0.04*	13.9	5.0
	Max. right thigh sway (deg)	17.4	14.9	0.31	11.7	7.0
	Max. sternum pitch angle (deg)	29.7	15.6	0.01*	16.3	11.1
	Max. sternum yaw angle (deg)	3.2	2.3	0.07	3.4	13.2
	Bicycle roll SD (deg)	1.2	0.3	0.09	1.3	0.3
	Max. left thigh sway acc. (deg/s^2)	1339	376	0.01*	894	197
	Right thigh sway acc. (deg/s^2)	1593	510	0.02*	1010	398
Obstacle avoidance	Max. sway left thigh (deg)	13.0	4.2	0.05*	8.5	3.4
	Max. acc. Sway right thigh (deg/s^2)	2256	1254	0.02*	1258	326
	Min. sternum pitch angle (deg)	4.6	2.3	0.09	7.2	3.0
	Lateral sternum acc. (deg/s^2)	2.9	1.3	0.01*	2.1	0.9
	Sternum yaw acc. (deg/s^2)	1044	436	0.07	800	391
Dismounting	Time spent on one leg (s)	2.9	0.7	0.01*	2.0	0.5
	Bicycle roll mean (deg)	−0.9	1.1	0.03*	0.7	2.0
	Steer angle mean (deg)	52.0	10.7	0.02*	20.6	27.8
	Max. steer acc. (deg/s^2)	489	114	0.09	1791	666

(SD 0.6) seconds compared to 2.4 (SD 0.7) seconds, respectively. The participants demonstrated a higher maximum bicycle roll angle for the SOFIE bicycle while the maximum bicycle steer angle was lower than on the normal bicycle. Furthermore, the maximum angular acceleration for the sternum roll and pitch and the thigh sway (lateral motion) were lower on the SOFIE bicycle. For dismounting the maximum steer angular acceleration tended to be higher for the SOFIE bicycle compared to the normal bicycle. Table 3 includes results of the statistical significant differences between the normal and SOFIE bicycle. The video analysis demonstrated less leg and steering motion with less sway across the road for the SOFIE bicycle compared to the normal bicycle during mounting and dismounting.

3.3.2. Straight cycling

During straight cycling at comfortable and slow cycling speeds, the SOFIE bicycle showed statistically significant higher variability (in terms of SD) compared to the normal bicycle for the bicycle roll angle, roll angular velocity and steer angular velocity and steer angular acceleration. On the contrary, the maximum steer angle was statistically significantly lower (Fig. 5, Table 3). Also the variability and the maximum values of the thigh sway angle and angular acceleration were lower on the SOFIE bicycle compared to normal bicycle. Compared to comfortable cycling speed, the variation in steer increased on average from 3.3 ° to 6.8 ° for normal bicycle and up to 8.6 ° for SOFIE bicycle (Fig. 5), though the thigh motions did not increase for slow cycling speeds.

3.3.3. Obstacle avoidance

Statistical analysis showed significantly less yaw motion of the thigh (p 0.05) and lower maximum values for the lateral acceleration of the sternum and thigh yaw angular acceleration (Table 3).

To avoid the obstacle, the cyclist needs to steer to change his path. To be able to pass the obstacle on the right side, one starts by steering slightly to the left so that the bicycle obtains a falling motion (a roll acceleration) to the right. This is what Kooijman calls 'Steer into the fall' (Kooijman et al., 2011). After initiating this rolling movement, one leans into the curve, steers to the right, and is able to avoid the object on the right side. During this motion one sways somewhat lateral to the left and then lateral to right over the road. Hence, the avoidance maneuver requires space on the road to be able to perform the avoidance successfully. The video analysis showed, that the SOFIE bicycle needs less time steering into the fall, needs less space on the road and is quicker to avoid the obstacle. Although not within the scope of this study, but important for bicycle handling, younger cyclists experimented with the maximum speed with which it was possible to avoid the obstacle: It was possible to make a sudden maneuver to avoid the obstacle up to speeds of 25 km/h on the SOFIE bicycle, whereas on the normal bicycle, a maximum speed of about 20 km/h was possible to successfully avoid the obstacle.

4. Discussion

The aim of this study was to register and analyse the performance of the SOFIE bicycle in terms of older cyclist safety and overall user-acceptance. In general, the SOFIE bicycle performance was similar or superior to the performance of the normal bicycle in critical cycling situations such as (dis-)mounting and avoiding an obstacle. User-acceptance of the SOFIE bicycle was good.

The subjective questionnaire and User-acceptance score showed a positive attitude towards the SOFIE bicycle for 5 of the 9 participants. Only two ladies scored a negative user-acceptance

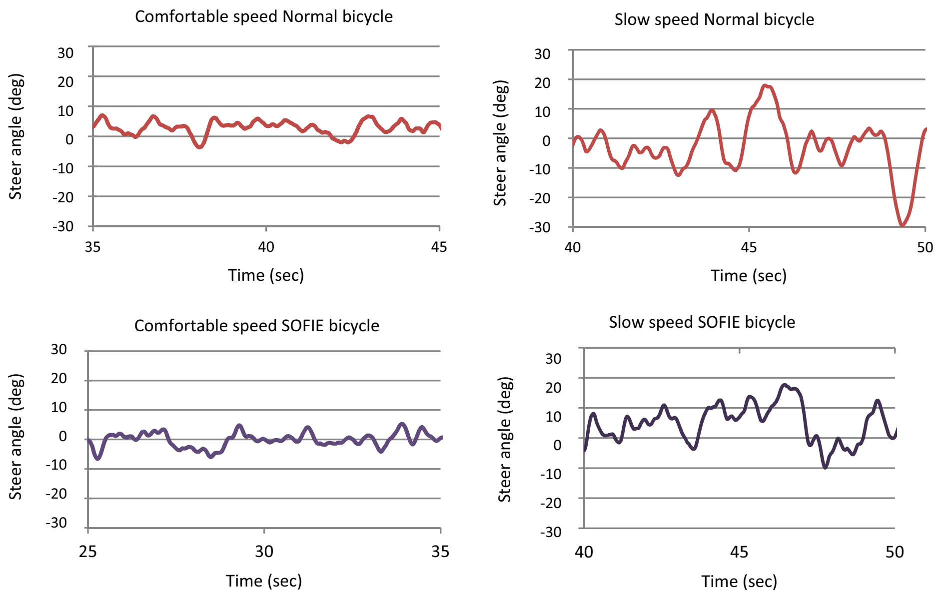

Fig. 5. Example of steering angle (degree) as function of time (seconds) during comfortable (left graphs) and slow (right graphs) straight cycling. The upper two graphs are data for the normal bicycle and lower two graphs for SOFIE bicycle. Each graph display random 10 s of straight cycling tasks.

due to a negative sub-score for "Satisfying". They scored the SOFIE bicycle as 'not desirable'. On questioning, the ladies mentioned "The bicycle has potential and may be beneficial for older cyclists, but for myself the bicycle is not necessary, I have no trouble mounting or dismounting". Even though the automatic saddle adjustment may not be necessary in terms of (experienced) safety, it does offer a lot of comfort and may contribute to safety during (dis-)mounting. Also younger cyclists who tested the bicycle were positive about the possibility of remaining on the saddle when stopping. However, it may take more 'practice time' in real life for the older cyclists to fully acknowledge the advantages of such a support system and relinquish familiar behaviour.

The time spend on one leg during (dis-)mounting was less for SOFIE compared to normal bicycle. Hence the time in unbalanced posture is less, reducing the risk of a possible fall caused by a disturbance. We did not observe significant difference in thigh motion, but sternum roll angular acceleration was lower for SOFIE bicycle during (dis-)mounting. So less muscle force would be required to keep the upper body upright. Many older people have muscle weakness, trouble standing on one leg (part of Berg Balance Score measuring fall risk) (Berg et al., 1989) and have stiff knees and hips. At a certain point, they may require a low step-through to facilitate maintaining balance during the mounting of the bicycle.

The older participants demonstrated less lateral leg motion when cycling on SOFIE compared to normal bicycle at comfortable and slow cycling speeds: The thigh yaw angle and angular acceleration were lower. According to the strategies cyclists demonstrate to maintain balance (Schwab et al., 2012), this would suggest that the cyclist is more balanced on the SOFIE bicycle, or that it is more effective to use other methods, like steering, to maintain balance. The SOFIE bicycle is designed to be self-stable at lower cycling speeds: that means that it will not fall over if pushed at that speed. The slow cycling speed may have been too high (8–9 km/h) to observe more pronounced changes in balance strategies, which may be observed on normal bicycles at speeds less than 5 km/h (Moore et al., 2011).

Maneuvering at higher speeds felt better on the SOFIE bicycle compared to the normal bicycle: many participants recommended how quick the bicycle was in changing directions without needing much space on the road or feeling unstable. This could be recognised in the video when analyzing the sudden obstacle avoidance. In the kinematic data, this effect seems to be reflected in lower roll and yaw angular velocities and angular accelerations of the sternum and thigh of the cyclist. The kinematics of the bicycle, however, did not differ significantly between the two bicycles during obstacle avoidance.

The participants had sufficient time to get acquainted with the SOFIE bicycle. However, the behaviour of the participants during the tests remained to some extent unsure and inconsistent, i.e. they would fall back into their familiar cycling behaviour. In such cases, we asked the cyclist to repeat the task. Furthermore, the participants (aged 67–79 years old) represented 'older cyclists', but most of them were still physically and mentally fit and had no problems with the cycling tasks. Previous accident analysis and kinematic cycling studies showed that also this age group demonstrates potential risk during cycling and (dis)mounting (Bulsink et al., 2016; Dubbeldam et al., 2014, 2015, 2016; Schepers and Klein-Wolt, 2012). But an older age group or a less fit group might have shown an even clearer benefit in cycling behaviour on the SOFIE bicycle compared to the normal bicycle. Therefore, the results of this study may be an under representation of the real potential of the tested support systems for the older senior population.

The SOFIE bicycle was tested in critical situations simulating real life in a safe way. The bicycle was a prototype and could not be tested in real life yet. In future, also the value of other support systems focussing on behaviour, such as navigation or warning systems, should be tested. Such tests may demonstrate the strengths and potential weaknesses of such systems and result in better insight of the working mechanisms. Ultimately, real-life tests need to be performed to evaluate support systems in daily life.

5. Conclusions

Several simple adjustments and add-ons to standard bicycles may enable safer and more comfortable cycling for older cyclists. The geometry of the SOFIE bicycle enabled faster (dis)mounting and lower leg and upper body angular accelerations during various cycling tasks. The automatic height adjustable saddle enabled a safer (dis-)mounting strategy. The drive-off support by the electric motor as well as the bicycle geometrical design resulted in lower maximum steer angles and less sway over the road. In general, the

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older participants recognised and praised the advantages of the SOFIE bicycle and user-acceptance was good.

Acknowledgements

We would like to thank our students Tim Pelle and Paul Straathof for their valuable support during the experiments and data processing. This study was funded by the Ministry of Economic Affairs grant number pid101047.

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