Transportation Research Part F 42 (2016) 28–43

Contents lists available at ScienceDirect

Transportation Research Part F

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

Riding performance on a conventional bicycle and a pedelec in low speed exercises: Objective and subjective evaluation of middle-aged and older persons

N. Kovácsová [a,*], J.C.F. de Winter [a], A.L. Schwab [a], M. Christoph [b], D.A.M. Twisk [b], M.P. Hagenzieker [b,c]

[a] Delft University of Technology, Department of Biomechanical Engineering, Mekelweg 2, 2628 CD Delft, The Netherlands
[b] SWOV Institute for Road Safety Research, PO Box 93113, 2509 AC The Hague, The Netherlands
[c] Delft University of Technology, Department of Transport & Planning, Stevinweg 1, 2628 CN Delft, The Netherlands

ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form 5 June 2016
Accepted 21 June 2016
Available online 6 August 2016

Keywords:
Steering performance
Self-reported skills
Age differences
Electric bicycle
Cycling

ABSTRACT

This study investigated cycling performance of middle-aged (30–45 years old; $n = 30$) versus older (65+ years; $n = 31$) participants during low-speed tasks for which stabilization skills are known to be important. Additionally, participants' self-ratings of their cycling skills and performance were assessed. Participants rode once on a conventional bicycle and once on a pedelec, in counterbalanced order. Three standardized tasks were performed: (1) low-speed cycling, (2) acceleration from a standstill, and (3) shoulder check. During Tasks 1 and 3, the mean absolute steering angle (a measure of the cyclist's steering activity) and the mean absolute roll rate (a measure of the amount of angular movement of the frame) were significantly greater for older participants than for middle-aged participants. These large lateral motions among older cyclists may indicate a difficulty to control the inherently unstable system. Comparing the conventional bicycle and the pedelec, participants reached a 16 km/h threshold speed in Task 2 sooner on the pedelec, an effect that was most pronounced among the older participants. Correlations between skills assessed with the Cycling Skill Inventory and actual measures of cycling performance were mostly not statistically significant. This indicates that self-reported motor-tactical and safety skills are not strongly predictive of measures of actual cycling performance. Our findings add to the existing knowledge on self-assessment of cycling skills, and suggest that age-related changes in psychomotor and sensory functions pose hazards for cycling safety.

1. Introduction

Across the period 2000–2009, a steady decline in cycling fatality rates has occurred in Europe, but the number of seriously injured cyclists has actually increased in the Netherlands (see OECD/ITF, 2013 for international trends in cycling safety). When expressed per kilometer traveled by bicycle, older cyclists (aged 65 or over) are the most vulnerable group (SWOV, 2013). Factors that may explain the increase of seriously injured cyclists are (1) population aging associated with a decrease of physical and cognitive functions (increasing the likelihood of a crash) and an increase of fragility (increasing the likelihood

* Corresponding author.
E-mail address: nataliakovacsova@gmail.com (N. Kovácsová).

http://dx.doi.org/10.1016/j.trf.2016.06.018
1369-8478/

of injury in case of a crash) (OECD, 2001), (2) changes in the types of bicycles used (e.g., conventional bicycles vs. pedelecs), and (3) growing exposure because an increasing number of trips are completed and longer distances are traveled on (electric) bicycles (Fyhri & Fearnley, 2015). This paper presents the results of a field experiment investigating self-reported and actual performance among middle-aged and older cyclists. Cycling performance on both a pedelec and a conventional bicycle was investigated during low-speed tasks for which stabilization skills are known to be important.

1.1. Potential risks of pedelecs for older persons

Pedelecs (also called electric bicycles or e-bikes) have gained enormous popularity in the last decade. About 5% of people in the Netherlands own a pedelec, with a relatively high rate of ownership and usage among women and people aged 60 and over (Van Boggelen, Van Oijen, & Lankhuijzen, 2013). A high usage of pedelecs among older people has also been observed in Austrian and German studies (GDV, 2014; Wolf & Seebauer, 2014).

Although pedelecs provide benefits to older persons, there are some safety concerns for this age group. It is well known that older people have less accurate sensory abilities (i.e., visual, vestibular, and somatosensory) and slower average reaction times than young persons (e.g., Jensen, 2006; Shaffer & Harrison, 2007). Therefore, older persons may have difficulties in situations that require agile reactions and active (low-speed) stabilization of the bicycle. Furthermore, age is associated with a decline of physical strength (Kallman, Plato, & Tobin, 1990).

A case control study by Schepers, Fishman, Den Hertog, Klein Wolt, and Schwab (2014) showed that people using pedelecs, after controlling for age, gender, and exposure, were more likely to be involved in a crash that required treatment at an emergency department than people using conventional bicycles. Moreover, analyses of crash characteristics have shown that pedelecs are involved in a disproportionally high number of single bicycle crashes, suggesting that cycling at high speed, mounting and dismounting, or difficulty in maneuvering may be causal factors (Papoutsi, Martinolli, Braun, & Exadaktylos, 2014; Schepers et al., 2014; Weber, Scaramuzza, & Schmitt, 2014).

1.2. The distinction between riding skill and riding style

Both riding skill ('performance') and riding style ('behavior') are crucial for assessing a person's cycling safety (for a review on skill versus style, see Elander, West, & French, 1993). Riding style refers to an individual's habits and preferences in riding the bicycle, such as crossing behavior at intersections and speed choice. Comparisons between the cycling speeds of conventional bicycles and pedelecs have shown that participants on pedelecs adopt an average cruising speed that is 1.5–4 km/h higher than on conventional bicycles (Dozza, Bianchi Piccinini, & Werneke, 2016; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, in press; Vlakveld et al., 2015).

Rider skill refers to how good a person is at controlling the vehicle (e.g., accelerating, steering) and at maneuvering in accordance with the prevailing circumstances on the road (e.g., avoiding an obstacle) (Michon, 1985). Cyclists balance the bicycle-rider system by means of two primary control mechanisms: steering and leaning (Kooijman & Schwab, 2013). The corresponding control inputs are the steering torque (applied by the cyclist through the handlebar) and the upper body lean torque (applied by the cyclist by leaning relative to the bicycle; Schwab, Kooijman, & Meijaard, 2008). Observations of a cyclist riding through a town showed that little upper body lean occurred when performing normal maneuvers and that the cyclist mainly used steering as control input (Kooijman, Schwab, & Moore, 2009).

Rider performance is typically evaluated by means of measures related to the steering and roll angle of the bicycle. The steering angle represents the rotation of the front assembly with respect to the bicycle frame, and the roll angle represents the left/right rotational movement of the bicycle frame about its longitudinal axis. Cain (2013) showed that the correlation between steer and roll angular velocities increased among children during the learning process, indicating that children learned to steer in the direction of roll. Fonda, Sarabon, and Li (in press) found that experienced cyclists had steer and roll motions of a smaller amplitude and of a lower rate than inexperienced cyclists. The previous studies that investigated how people control a bicycle have been conducted on children and middle-aged cyclists. It is yet unknown how an age-related decline in motor, sensory, and cognitive functioning is associated with rider performance.

Thus far, research on individual differences in rider performance for different types of bicycles has been sparse. Some experimental studies have been conducted with the purpose of evaluating the effects of bicycle design on handling performance (e.g., Godthelp & Wouters, 1980; Mortimer, Domas, & Dewar, 1976; Rice & Roland, 1970). These studies showed that humans are capable of successfully riding bicycles with different handlebar configurations and different basic designs of bicycles, which suggests that cyclists may be able to successfully transfer their riding skills from a conventional bicycle to a pedelec. Although conventional bicycles and pedelecs have similar dimensions, due to their battery and motor, pedelecs are typically heavier than conventional bicycles (MacArthur & Kobel, 2015).

1.3. Self-assessment of skill

The self-assessment of skills has an important role in so-called 'calibration', a process whereby a rider adjusts the task demands to his/her perceived skills, and which is assumed to be essential in road safety (Kuiken & Twisk, 2001). Moreover, it has been argued that the understanding of one's own capabilities plays an important role in the learning process and in the prevention of poor decision making and risky behaviors (Horrey, Lesch, Mitsopoulos-Rubens, & Lee, 2015; Keskinen & Hernetkoski, 2011; Kuiken & Twisk, 2001).

With the aim of investigating whether car drivers have an accurate perception of their own skills, several different methods have been used (Sundström, 2008). Sometimes (a) drivers had to compare their skills with the skills of the 'average driver' or their peers, (b) drivers had to rate their own skills on specific aspects of driving skill such as is in the Driving Skill Inventory (Lajunen & Summala, 1995), or (c) the self-reported skill was compared with actual driving performance. Research on the self-assessment of cycling skills is scarce. In early studies by Daniels, Zajkowski, and Drury (1976) and Drury and Daniels (1980), cyclists ($n = 25$) rated their riding skills (from extremely skilled to no skill) and cautiousness (from extremely cautious to not cautious) and performed four cycling exercises (slalom, circle speed, braking, and straight line tracking). Of the reported correlations between self-assessed skill/cautiousness and ten objective measures of riding speed and accuracy, only two correlations were statistically significant: self-rating of skill correlated positively with average speed in a circle exercise, and self-rating of caution correlated negatively with stopping distance. These findings suggest that self-assessment of cycling skill might not be strongly predictive of actual cycling measures.

1.4. The present study

The study in this paper is part of a larger field operational test with an instrumented conventional bicycle and a pedelec conducted at the SWOV Institute for Road Safety Research in the Netherlands from July until September 2013. The aim of this field test was to assess the effect of pedelecs on cycling performance and behavior among middle-aged versus older persons, with an emphasis on cycling safety. The field test consisted of a 30-min ride on a pedelec and a 30-min ride on a conventional bicycle. After each of these two rides, the participants conducted standardized exercises on an empty parking lot. In addition to collecting objective data measured by devices mounted on the bicycles, questionnaires were administered prior and after the field testing, and cyclists' workload, balance, and grip strength were measured.

Previous publications on this field test have focused on rider behavior (speed choice) and workload during the 30-min rides (Vlakveld et al., 2015), on the specific procedures during mounting maneuvers in relation to rider speed and balance (Platteel, Twisk, & Lovegrove, 2015), and on self-reported skills of older versus middle-aged cyclists (De Groot-Mesken & Commandeur, 2014). The present study focuses on cyclists' performance during three exercises on an empty parking lot: (1) low-speed cycling, (2) acceleration from a standstill, and (3) shoulder check. Our first aim was to investigate cyclists' performance regarding the control of a conventional bicycle and a pedelec, and to establish how this performance is associated with participants' age, reaction time, and grip strength. The second aim was to investigate how rapidly cyclists accelerate, and which speeds they adopt during these exercises. The third aim was to assess cyclists' self-ratings of their general cycling skills and performance during the field test, and to examine the correlation between general cycling skills and actual cycling performance. Specifically, this study addressed the following four research questions.

(1) How is age associated with cycling performance and speed?
(2) Do participants on a pedelec adopt different speeds than the same participants on a conventional bicycle?
(3) How strongly are self-reported general cycling skills correlated with actual cycling performance?
(4) Do participants believe that they performed particular skills better on the conventional bicycle than on a pedelec, or vice versa?

2. Method

2.1. Participants

Sixty-one participants were recruited through invitation letters, flyers, and the SWOV research participant database. Addresses for dissemination of the invitation letters were obtained from a marketing/communication company based on two age groups (30–39 vs. 65–79 years) and living area (The Hague and its surroundings). Five hundred letters were sent to the middle-aged group and another 500 letters were sent to the older-age group. Only persons who cycled regularly and who were in good health were eligible to participate. Pedelec riding experience was not required (1 middle-aged and 9 older participants reported that they own a pedelec). Moreover, only persons who were either 30–45 years old or 65 years old or older were included in the study.

Demographic characteristics of both age groups are shown in Table 1. One participant withdrew from the study due to safety reasons and one participant was excluded from the analyses because of a failure of the speed-measuring device. In addition, one participant was excluded from the analyses of Task 2 because of not performing the task correctly. Seven participants were excluded from the analyses for Task 3 due to technical problems with the rider-facing camera (1 participant), not performing the task correctly (2 participants), and participants' withdrawal from the task (4 participants). The withdrawn participants considered the task as difficult and decided to not complete the task after (a) hearing the instruction (1 participant) or (b) an incorrect first try (3 participants).

Table 1
Demographic characteristics of the participants for Tasks 1, 2, and 3.

Age group	Characteristics	Total sample	Task 1 *Low-speed cycling*	Task 2 *Accelerating*	Task 3 *Shoulder check*
Middle-aged participants	*N*	30	30	30	29
	Females	17	17	17	17
	Mean age (*SD*)	37.7 (4.2)	37.7 (4.2)	37.7 (4.2)	37.7 (4.3)
Older participants	*N*	31	29	28	23
	Females	14	13	12	9
	Mean age (*SD*)	70.0 (4.2)	69.9 (4.2)	69.6 (3.9)	69.6 (3.8)

2.2. Data collection and procedure

Prior to the test day, participants received a self-report questionnaire with items on demographic characteristics, travel behavior, and skills (Cycling Skill Inventory; De Groot-Mesken & Commandeur, 2014). At the beginning of the testing session, the details of the study were explained to the participants, after which an informed consent form was signed[1]. Prior to riding the instrumented bicycle, participants' grip strength and baseline reaction times on the peripheral detection task (PDT) were measured (see Vlakveld et al., 2015 for a description of PDT). Next, participants were equipped with the bicycle helmet, PDT equipment, and a backpack.

The field experiment was conducted in daylight and dry weather conditions. Each participant rode the approximately 3.5 km long route four times: one practice ride and one test ride on both the conventional bicycle and pedelec. After the test ride on each bicycle, participants were asked to perform four standardized tasks on the parking lot area: (1) cycling at low speed, (2) accelerating up to 17 km/h and then brake, (3) indicating direction with the left hand and looking backwards, (4) mounting and dismounting. Thus, a participant rode a practice ride, a test ride, and performed tasks on the empty parking lot on the one type of the bicycle (i.e., conventional bicycle or pedelec). After this, the participant returned to the starting point to change the bicycle and repeated the procedure with the other type of bicycle. The order of bicycle type was counterbalanced across participants. The first three tasks on the parking lot were analyzed in the present study. The PDT device was switched off during the parking lot exercises. For a detailed description of the 3.5 km long route, see Vlakveld et al. (2015).

At the end of the experiment, a final questionnaire on the participants' performance when riding both bicycle types (Cyclist Self-Assessment Scale) was administered. Each session lasted approximately 2.5 h and at the end, participants were reimbursed for their time with a gift card. All instructions and questionnaires were provided to the participants in the Dutch language.

2.3. Apparatus

Cycling data were collected by two instrumented bicycles (see Fig. 1), which were the same model with step-through frame. The pedelec was a Batavus Socorro Easy model 2012. This bicycle had a rear wheel hub motor that could deliver a maximum power of 250 W and a maximum torque of 40 Nm. The electrical assistance was controlled by a pedal force sensor. The pedelec weight was 27.4 kg and was 11.4 kg heavier than the conventional bicycle. The electric engine provided pedaling assistance only when the cyclists pedaled and only up to a speed of 25 km/h. Power support could be set to four levels: no support, low support, normal support, and high support. In the present study, 'normal support' was set and participants were requested to not change this during the whole experiment. Each bicycle had 21 gears. Participants were allowed to change gears when riding the conventional bicycle. However, participants were asked to not change gears when riding the pedelec. The gear ratio influences the force that participants put on the pedals, which in turn determines the power supplied by the support system. By keeping the gear ratio constant, all participants received the same amount of pedaling support at a given speed.

For measuring steering angle, a potentiometer with angular range up to 360 degrees was mounted at the steering shaft. To measure the roll rate of the bicycle, a single axis sensor (Silicon Sensing CRS03) mounted on the back of the bicycle was used. Speed was measured with a generator embedded in the hub of the front wheel. Steering angle, roll rate, and speed data were logged at a sampling rate of 50 Hz. To inform cyclists about their speed, a display was mounted on the handlebar.

2.4. Description of the tasks

The tasks conducted on the parking lot area were offered to all participants in the same order. The instruction for each task was provided after completing the previous task. In case a participant did not complete a task correctly for the first time,

[1] ***Ethical Considerations.*** The experiment was performed in compliance with all relevant Dutch legislation. At the time of the experiment, the performing institute SWOV Institute for Road Safety Research did not have an approving institutional review board. However, the study was planned so as to strictly follow the guidelines for ethical conduct of behavioral projects involving human participants proposed by the American Psychological Association. Participants' data protection complies with the rules of the Dutch Data Protection Authority (Dutch DPA).

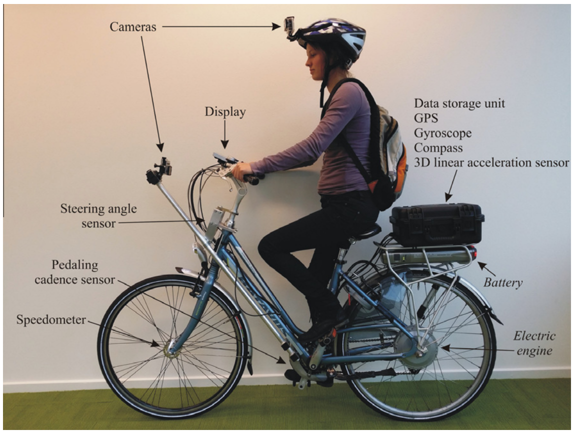

Fig. 1. The instrumentation of the pedelec. The instrumented conventional bicycle was not fitted with the battery and electric engine (indicated in italics).

two more tries were offered (one more try for Task 3). In all tasks, participants were instructed to ride straight ahead but no straight-line markers on the ground were available.

The instruction and exclusion criteria for each task were as follows:

2.4.1. Task 1: Low-speed cycling

The instruction for the participants was the following: "*When I whistle, start cycling slowly at 7 km/h until you reach the last pylon. Next, you can turn around and cycle back at your own pace.*"

2.4.2. Task 2: Accelerating

The participants received the following instruction: "*Try to reach a speed of 17 km/h as quickly as possible and subsequently come to standstill by braking as hard as possible. You do not have to get off the bike.*" Due to large individual differences in braking (from rapid/immediate braking to slow/continuous braking), only the acceleration part was analyzed in the present study. One participant was excluded because she did not reach the instructed speed.

2.4.3. Task 3: Shoulder check

The participants were instructed as follows: "*When I whistle, start cycling at your own pace. When passing the first traffic pylon, please indicate direction with your left hand, and when I whistle again look over your left shoulder. Try to see how many hands I raise* (*zero, one, or two*)". Fig. 2 shows an overview of the subtasks of Task 3. It should be noted that there were individual differences in the way participants carried out the particular subtasks. Left-hand-turn and looking-over-the-left-shoulder events were coded based on the videos recorded by the rider-facing camera. Two participants were excluded because they did not continue straight after performing the subtasks, that is, started to turn the bicycle to the left while looking backwards and/or indicating direction by hand. Participants who did not report correctly how many hands the experimenter raised but otherwise performed the exercise correctly were not excluded (6 participants).

2.5. Measures

2.5.1. Cycling performance

The following cycling performance measures were calculated for each task, for each participant, and for both bicycles:

Mean absolute steering angle (deg). This measure is the absolute steering angle averaged across time. A large mean absolute steering angle might indicate difficulty in balancing and controlling the bicycle when cycling straight.

Mean absolute roll rate (deg/s). The mean absolute roll rate was used as a measure of the lateral movement speed of the bicycle frame. The bicycle roll rate is closely linked with steer rate as well as with pedaling activity (Moore, Kooijman, Schwab, & Hubbard, 2011). A large mean absolute roll rate might indicate difficulties with stabilizing the bicycle.

R^2 between roll rate and steering rate (between 0 and 1). The peak value of the cross-correlation between roll rate and steering rate was squared to yield a R^2, being a measure of the similarity between the two signals. The same way of calculating the cross-correlation between bicycle roll rate and steer rate was also used in a previous study on cyclists' performance (Cain, 2013). This measure was calculated only for Task 1 since it was the only task in which the participants rode the bicycles at constant speed across the whole exercise.

Time delay between roll rate and steering rate (s). The corresponding time delay is a measure of how much the steering signal lags behind the roll signal. This measure was calculated also only for Task 1.

Mean speed (km/h). The mean speed was used as a measure of cycling speed.

Total time (s). The total time was used as a measure of time to complete the (sub)task.

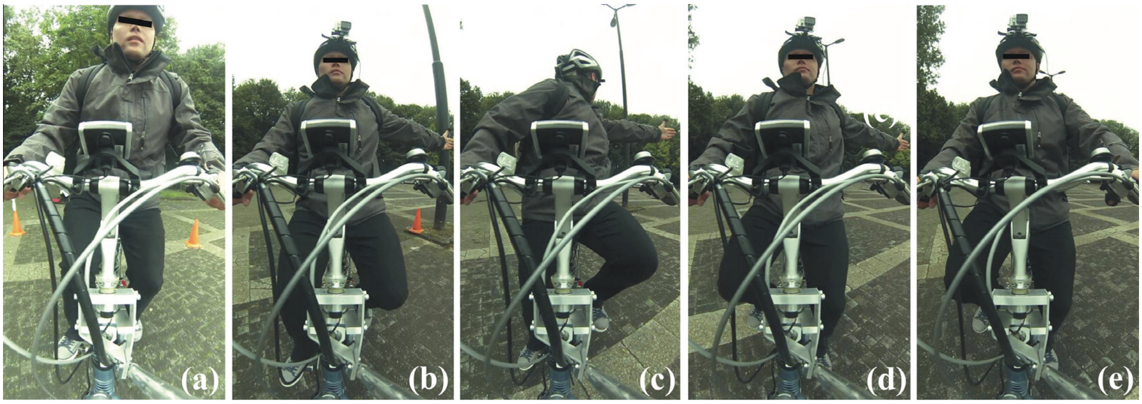

Fig. 2. Task 3: Shoulder check; (a) straight cycling, (b) indicating direction with the left hand while looking to the front, (c) looking over the shoulder, (d) looking again to the front while still indicating direction, (e) straight cycling with both hands on the handlebar.

For Task 1 (low-speed cycling), since the speed and total distance slightly varied across the participants, some participants completed the task in a shorter time than others. In order to have the same amount of data for each participant, data from 5 up to 20 s (approximate time when all participants had reached the instructed speed of 7 km/h) were analyzed. For Task 2 (accelerating), the above measures were analyzed from the moment the participant rode faster than 0 km/h until reaching 16 km/h. The threshold speed used in the analysis was set at 16 km/h instead of the instructed speed of 17 km/h in order to apply a small buffer that can account for a potential difference/lag between the actual speed and the speed displayed by the device on the handlebar. For Task 3 (shoulder check), the analysis was divided into two parts: (1) '3 s before head start – head start' and (2) 'head start – head end'. This way, we made a distinction between a 3 s relatively stationary period *prior* to head/body movement, and the period *during* head/body movement.

2.5.2. Self-reported cycling skills and performance

The Cycling Skill Inventory (CSI; De Groot-Mesken & Commandeur, 2014) is a 17-item scale for assessing an individual's self-reported cycling skills. The CSI was developed based on the taxonomy of motor skills and safety skills that is typically found among car drivers (Lajunen & Summala, 1995). The CSI items were produced by selecting items from Lajunen and Summala's Driver Skill Inventory (DSI) that are relevant also to cyclists (e.g., "knowing how to act in particular traffic situations") and by creating several new skill items that are cycling-specific (e.g., "cycling when it is slippery"). Participants were asked to compare themselves with an average cyclist of the same age. The response options for each item were: 1 (*much better*), 2 (*better*), 3 (*the same*), 4 (*worse*), and 5 (*much worse*).

In another questionnaire – Cyclist Self-Assessment Scale (CSAS), participants rated their performance during their test rides (i.e., 3.5 km rides and exercises on a parking lot) after the entire field testing for the conventional bicycle versus the pedelec. This scale was developed to assess self-ratings of the particular tasks that were performed in the field test. Participants were required to tick a bullet on a seven-point scale (without numbering), in which one pole was the conventional bicycle and the other pole the pedelec. The closer participants indicated their response to one type of bicycle, the more they believed they were able to perform the particular skill better during their test rides on this bike. Response place in the middle of the scale indicated that participants were able to perform the skill equally well on both bicycles. Only items that were related to the first three tasks were analyzed; they were as follows: accelerating from standstill, bicycle control, turning, braking/stopping, keeping balance, and obtaining/maintaining speed.

2.5.3. Grip strength and reaction time

The participants' grip strength was recorded using a dynamometer. The handle grip of the dynamometer was adjusted to ensure that it is comfortable in the hand of the participant. The participants were asked to squeeze as hard as possible for about 2 s. The task was performed twice for each hand with a resting period of 15–20 s.

The participants' baseline reaction time was measured using the PDT device while participants were standing next to the bicycle prior to the first practice ride. Participants were asked to respond to the LED light as quickly as possible by pushing a button. The LED light was switched on for 1 s at a time. The inter-stimulus interval was 3–5 s (determined at random) and the task lasted three minutes in total. Thus, a participant performed about 36 reaction time trials in total.

2.6. Statistical analyses

First, cycling experience, grip strength, and reaction time among the two age groups were described using the mean and standard deviation. Differences for age were analyzed with independent two-sample t tests. The grip strength was averaged across four trials, and the baseline reaction time was averaged across approximately 36 trials.

Next, the factor structure of the Cycling Skill Inventory was assessed. Items of the CSI were subjected to principal axis factor analysis (PAF) followed by direct oblimin rotation. PAF is one of the most common types of exploratory factor analysis (Conway & Huffcutt, 2003; De Winter & Dodou, 2012). Exploratory factor analysis is a statistical method that attempts to explain the off-diagonal elements of correlation matrix in terms of a small number of common factors; it closely resembles principal component analysis, which is essentially a data reduction method. A minimum factor loading of .30 was used for considering an item to be part of a factor. The mean scores of the CSI factors and the CSAS items were compared between middle-aged and older participants using an independent two-sample t test. In addition, frequencies of self-ratings of participant's cycling performance (CSAS) were calculated.

A data quality check revealed that there were some differences in the characteristics (e.g., noise characteristics) of the steering angle and roll rate measurements between the two bicycles. Because even the slightest difference in calibration, sensor fabrication, or sensor attachment would invalidate conclusions, we refrain from interpreting steer and roll differences *between* the conventional bicycle versus pedelec on the steering and roll rate measures. However, any age effect should still be valid, because all participants rode both bicycles, and because middle-aged and older participants were sampled more or less alternately (i.e., there was no correlation between participant number and age [$r = 0.01$, $N = 61$]).

Prior to the statistical analysis of the data collected on instrumented bicycles, the steering, roll rate, and speed signals were filtered with a forward and reverse low-pass filter with a cut-off frequency of 7.5 Hz, 7.5 Hz, and 2.5 Hz, respectively.

Differences between middle-aged and older cyclists in steer and roll rate measures (averaged across both types of bicycles) were analyzed with independent two-sample t tests. The mean speed averaged across the time of the (sub)task and time to complete the (sub)task of older participants on a conventional bicycle and a pedelec were compared to those of middle-aged participants. A 2×2 mixed design analysis of variance (ANOVA) was performed, with (1) bicycle type (conventional bicycle vs. pedelec) as within-subjects factor, (2) age (middle-aged vs. older participants) as between-subjects factor, and (3) bicycle type $\times$ age group as interaction factor.

In order to explore the relationships between demographic variables, cycling frequency, weekly distance traveled, grip strength, reaction time, self-reported cycling skills (measured by the CSI), and actual cycling performance, Spearman's rank order correlation coefficients were computed. In calculating these correlation coefficients, the cycling performance measures were averaged across both types of bicycles.

3. Results

3.1. Descriptive results

Descriptive statistics for cycling experience, grip strength, and reaction time are presented in Table 2. Middle-aged participants rode their bicycle more often than older participants did. Middle-aged cyclists squeezed the dynamometer significantly harder than older cyclists. The mean z-scores of the grip strength with respect to published age- and gender-based norms of grip strength (Dodds et al., 2014) were -0.48 ($SD = 0.85$, $N = 30$) for the middle-aged participants and -0.56 ($SD = 0.77$, $N = 31$) for the older participants. Differences in reaction time between two age groups were not statistically significant.

3.2. Self-rating of cycling skills

The scree plot (i.e., the eigenvalues of the correlation matrix) of the 17 CSI items indicated that a two-factor solution was most appropriate (the first four eigenvalues were 7.33, 2.83, 1.23, and 1.07). The two-factor solution accounted for 54.9% of the variance: 40.8% and 14.1% for Factor 1 and Factor 2, respectively. The factor loadings are shown in Table 3. The first factor consisted of twelve items, which reflect vehicle handling skills and perceptual and social skills related to prevailing circumstances on the road and thus the factor was labeled as 'motor-tactical skills' based on terminology proposed by Michon (1985). The second factor consisted of five items that are similar to the original safety skills factor found among car drivers (Lajunen & Summala, 1995). Thus, this factor was labeled 'safety skills'.

Table 2
Means, standard deviation, and t tests for cycling background variables, grip strength, and reaction time according to age group.

	Middle-aged			Older			Middle-aged vs. older	
	N	Mean	SD	N	Mean	SD	t (df)	p
Kilometers per week	30	43.4	40.2	29	30.1	32.5	1.400 (57)	0.167
Cycling frequency*	29	4.21	1.01	30	3.47	1.22	2.525 (57)	**0.014**
Grip strength (N)	30	348.5	104.1	31	270.6	67.8	3.478 (59)	**<0.001**
Reaction time (ms)	29	292.7	72.9	31	315.2	75.0	−1.181 (58)	0.242

Note. p values < 0.05 are in boldface.

* Cycling frequency was indicated on a 5-point scale: 1: *less than once per month*, 2: *few times per month*, 3: *1–2 days per week*, 4: *3–4 days per week*, 5: *5–7 days per week*.

Table 3
Factor loadings, means, and standard deviations of the Cycling Skill Inventory items ($N = 60$).

Item	Middle-aged participants Mean (*SD*)	Older participants Mean (*SD*)	Motor-tactical skills	Safety skills
10. Fast reactions	2.43 (0.77)	2.27 (0.64)	**0.879**	0.019
9. Recognizing hazards in traffic	2.37 (0.76)	2.17 (0.65)	**0.839**	−0.030
15. Maneuvering smoothly through busy traffic	2.53 (0.78)	2.47 (0.73)	**0.821**	−0.163
5. Controlling the bicycle	2.53 (0.63)	2.40 (0.67)	**0.816**	0.149
7. Sudden braking and/or swerving when needed	2.47 (0.73)	2.17 (0.70)	**0.806**	0.190
2. Knowing how to act in particular traffic situations	2.47 (0.68)	2.57 (0.57)	**0.758**	−0.184
14. Predicting traffic situations ahead	2.43 (0.63)	2.33 (0.66)	**0.749**	0.053
17. Showing consideration for other road users	2.47 (0.68)	2.30 (0.60)	**0.679**	0.143
8. Staying calm in irritating situations	2.37 (0.67)	2.30 (0.79)	**0.547**	0.165
1. Cycling when it is slippery	2.90 (0.80)	2.93 (0.78)	**0.528**	−0.383
4. Tolerating other road users' errors calmly	2.63 (0.81)	2.63 (0.72)	**0.502**	0.079
11. Yielding to somebody else who does not have right of way	2.53 (0.73)	2.33 (0.71)	**0.462**	0.260
16. Obeying traffic rules	2.77 (0.68)	2.53 (0.68)	0.010	**0.901**
13. Cycling carefully	2.90 (0.71)	2.50 (0.68)	0.127	**0.682**
12. Avoiding unnecessary risks	2.67 (0.66)	2.43 (0.63)	0.200	**0.660**
6. Adjusting speed to the conditions	2.70 (0.88)	2.37 (0.67)	0.328	**0.627**
3. Obeying traffic signals	2.80 (0.76)	2.67 (0.61)	−0.112	**0.572**
% of variance explained			40.8	14.1
Cronbach's alpha[a]			0.92	0.84
Number of items			12	5
Mean (SD)[a]**: Middle-aged participants**			2.51 (0.56)	2.77 (0.61)
Mean (SD)[a]**: Older participants**			2.41 (0.47)	2.50 (0.47)

Note. Bold values refer to items with factor loadings of 0.3 or greater that were used in producing the composite scale (values of 0.3 or higher that are not in boldface indicate that the item was not used in producing the composite scale). Participants rated each item from 1 (*much better*) to 5 (*much worse*).
[a] Cronbach's alpha, mean, and standard deviation were calculated for the concerning scale.

There were no statistically significant differences between middle-aged and older participants for both extracted factors ($p > 0.05$). As can be seen in Table 3, participants rated their skills as slightly better than an average cyclist of the same age (i.e., mean score < 3 on the five-point scale).

The majority of middle-aged and older participants rated their 'accelerating from standstill' and 'obtaining/maintaining speed' performance as better when riding the pedelec compared to riding the conventional bicycle (see Table 4). In general, participants reported to be slightly better on the other four performed tasks when riding the conventional bicycle compared to the pedelec (except for 'braking/stopping' among older cyclists). No significant differences were observed between middle-aged and older cyclists for self-rated cycling performance across two bicycles ($p > 0.05$).

3.3. Actual cycling performance

The means and standard deviations of the cycling performance measures per age group and per bicycle are shown in Table 5. The results of independent two-sample *t* tests for the measures of steering and bicycle roll are also shown in Table 5, and a summary of the 2×2 mixed design ANOVA results for the speed and time measures is provided in Table 6.

3.3.1. Steering and roll

Participants in Task 1 performed relatively small mean steering actions (i.e., mean absolute steering angles around 3 deg, see Fig. 3, top left) while cycling at average speeds of about 7–8 km/h, which is a speed range for which human stabilizing is needed. Older participants had a significantly higher mean absolute steering angle than middle-aged participants while performing this task (means = 2.55 vs. 3.07 deg for middle-aged and older participants, respectively; $t(57) = -2.927$, $p = 0.005$).

Table 4
Frequency distribution and means for performance on both bicycle types rated after the field experiment for middle-aged and older cyclists.

	Middle-aged participants									Older participants								
	N	Frequency[a]							Mean	*N*	Frequency[a]							Mean
		1	2	3	4	5	6	7			1	2	3	4	5	6	7	
Accelerating from standstill	29	0	1	2	5	2	11	8	5.52	31	3	1	2	5	6	11	3	4.77
Bicycle control	29	1	7	6	13	2	0	0	3.28	31	3	3	4	12	4	3	2	3.90
Turning	30	1	1	11	14	2	1	0	3.60	31	2	2	8	12	2	4	1	3.84
Braking/stopping	30	2	2	2	22	2	0	0	3.67	31	1	2	0	22	2	4	0	4.10
Keeping balance	30	1	1	5	22	1	0	0	3.70	31	2	2	7	13	3	4	0	3.81
Obtaining/maintaining speed	30	0	1	0	5	5	10	9	5.67	31	0	2	0	4	8	13	4	5.35

[a] Each item was rated on a 7-point scale (without numbering), in which one pole was a conventional bicycle (1) and on the other pole was a pedelec (7). An answer placed in the middle of the scale (point 4) indicated that the skill was reported as executed equally well on both bicycles.

Table 5
Means and standard deviations of the dependent measures for the three tasks for middle-aged and older participants on the conventional bicycle and the pedelec (measures are averaged across time) and results of the *t* tests for steering and bicycle roll (the two bicycle types were aggregated).

	Conventional bicycle Middle-aged participants		Pedelec Middle-aged participants		Conventional bicycle Older participants		Pedelec Older participants		Both bicycle types Middle-aged vs. older		
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	*t* (*df*)	*p*	η^2
Steering performance											
T1: Mean absolute steering angle (deg) (5–20 s)	2.50	0.98	2.60	0.69	3.07	0.71	3.07	0.86	−2.927 (57)	**0.005**	0.131
T2: Mean absolute steering angle (deg) (0–16 km/h)	6.76	3.90	7.04	4.78	6.00	2.97	6.15	2.89	0.972 (56)	0.335	0.017
T3: Mean absolute steering angle (deg) (3 s before head start – head start)	1.83	0.48	1.80	0.53	2.18	0.57	2.49	1.52	−3.388 (50)	**0.001**	0.187
T3: Mean absolute steering angle (deg) (head start – head end)	3.34	2.15	2.85	1.67	4.23	2.24	4.18	2.36	−2.327 (50)	**0.024**	0.098
Bicycle roll											
T1: Mean absolute roll rate (deg/s) (5–20 s)	1.97	0.43	1.79	0.31	2.48	0.54	2.16	0.56	−4.013 (57)	**<0.001**	0.220
T2: Mean absolute roll rate (deg/s) (0–16 km/h)	7.04	2.84	5.71	2.01	6.79	1.79	6.08	1.81	−0.132 (56)	0.895	0.000
T3: Mean absolute roll rate (deg/s) (3 s before head start – head start)	3.81	0.95	3.80	1.24	3.68	0.99	4.36	1.35	−0.852 (50)	0.398	0.014
T3: Mean absolute roll rate (deg/s) (head start – head end)	5.27	2.19	4.95	1.85	6.06	1.89	6.79	2.47	−2.802 (50)	**0.007**	0.136
T1: Time delay between roll rate and steering rate (s)	0.16	0.04	0.14	0.04	0.13	0.03	0.12	0.03	2.827 (57)	**0.006**	0.123
T1: R^2 between roll rate and steering rate (0–1)	0.34	0.14	0.41	0.13	0.45	0.11	0.44	0.12	−2.405 (57)	**0.019**	0.092
Speed											
T1: Mean speed (km/h) (5–20 s)	7.60	0.66	7.42	0.37	7.93	0.85	7.62	0.71	–	–	–
T3: Mean speed (km/h) (3 s before head start – head start)	12.81	1.27	13.74	2.15	11.91	1.46	13.20	1.94	–	–	–
T3: Mean speed (km/h) (head start – head end)	12.18	1.72	13.09	2.54	11.58	1.60	12.52	2.29	–	–	–
Time											
T2: Time to reach 16 km/h (s)	4.28	1.17	3.79	1.03	6.10	1.93	4.26	1.50	–	–	–
T3: Time head start – head end (s)	2.14	0.72	2.10	0.70	2.40	0.61	2.36	0.76	–	–	–

Notes. T1 – Task 1: Low-speed cycling, T2 – Task 2: Accelerating, T3 – Task 3: Shoulder check; *p* values < 0.05 are in boldface. A positive *t* statistic means that middle-aged cyclists had a higher score than older cyclists and a negative *t* statistic means that middle-aged cyclists had a lower score than older cyclists.
'–' indicates that *t* test was not performed; see Table 6 for ANOVAs regarding the speed and time measures.

Table 6
Summary of ANOVA results regarding bicycle type, age group, and interaction between bicycle type and age group.

	Within-subjects effect				Between-subjects effect				Interaction effect		
	Bicycle type				Age group				Bicycle type ∗ Age group		
	F (*df*1, *df*2)	*p*	*MSE*	η^2	*F* (*df*1, *df*2)	*p*	*MSE*	η^2	*F* (*df*1, *df*2)	*p*	η^2
Speed											
T1: Mean speed (km/h) (5–20 s)	7.97 (1, 57)	**0.007**	0.22	0.122	3.09 (1, 57)	0.084	0.67	0.051	0.50 (1, 57)	0.484	0.008
T3: Mean speed (km/h) (3 s before head start – head start)	20.49 (1, 50)	**<0.001**	1.53	0.288	2.93 (1, 50)	0.093	4.56	0.055	0.55 (1, 50)	0.460	0.008
T3: Mean speed (km/h) (head start – head end)	11.01 (1, 50)	**0.002**	1.99	0.180	1.32 (1, 50)	0.255	6.71	0.026	0.00 (1, 50)	0.946	0.000
Time											
T2: Time to reach 16 km/h (s)	52.82 (1, 56)	**<0.001**	0.75	0.418	11.21 (1, 56)	**0.001**	3.37	0.167	17.41 (1, 56)	**<0.001**	0.138
T3: Time head start – head end (s)	0.12 (1, 50)	0.727	0.27	0.002	2.40 (1, 50)	0.127	0.72	0.046	0.00 (1, 50)	0.972	0.000

Notes. T1 – Task 1: Low-speed cycling, T2 – Task 2: Accelerating, T3 – Task 3: Shoulder check, *p* values < 0.05 are in boldface.

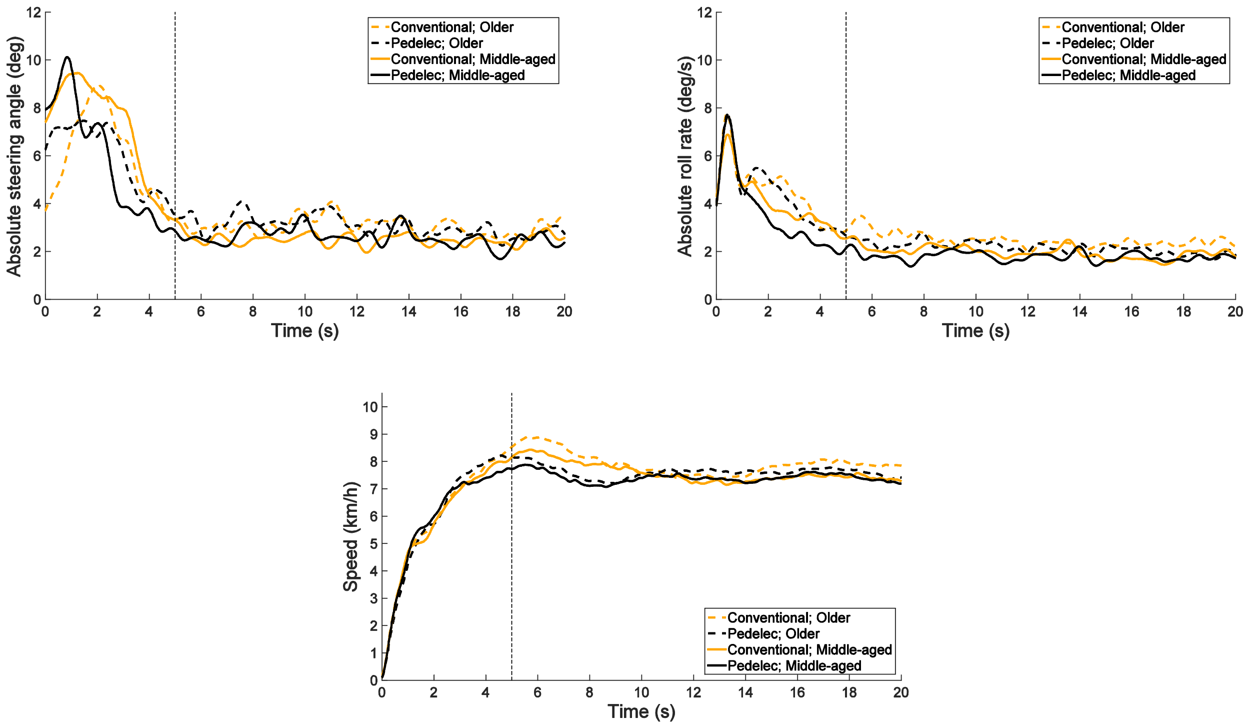

Fig. 3. Mean absolute steering angle (top left), mean absolute roll rate (top right), and mean speed (bottom) during low speed cycling (Task 1). The vertical dashed line indicates 5 s from the start, which is the moment from which data were used in the statistical analyses. For improved clarity of the figures, the absolute steering angle and the absolute roll rate were filtered with an additional low-pass (1 Hz cut-off frequency) forward and reverse filter.

The mean absolute roll rate reported in Fig. 3 (top right) was also significantly higher for the older participants (means = 1.88 vs. 2.32 deg/s for middle-aged and older participants, respectively; $t(57) = -4.013$, $p < 0.001$). R^2 values between roll rate and steering rate were significantly higher for older participants than for middle-aged participants ($t(57) = -2.405$, $p = 0.019$). Moreover, results showed significant differences between the two age groups in the delay between roll rate and steering rate ($t(57) = 2.827$, $p = 0.006$), in that the steering rate lagged the roll rate less among older participants compared to the middle-aged participants (Table 5).

The results of Task 2 clearly show that the average steering angle decreased with increasing speed (Fig. 4, top left). No significant differences were found between the two age groups in steering and bicycle roll measures in Task 2 (Table 5).

Regarding Task 3 the mean absolute steering angle was small (about 2–3 deg) prior to head turn but grew substantially during the head turn for both participant groups riding on two types of bicycles (Fig. 5, top left). This trend after the head turn was also observed for mean absolute bicycle roll rate (Fig. 5, top right). Participants' age had a significant effect on the mean absolute steering angle in both subtasks of Task 3 ($t(50) = -3.388$, $p = 0.001$ and $t(50) = -2.327$, $p = 0.024$, for subtasks

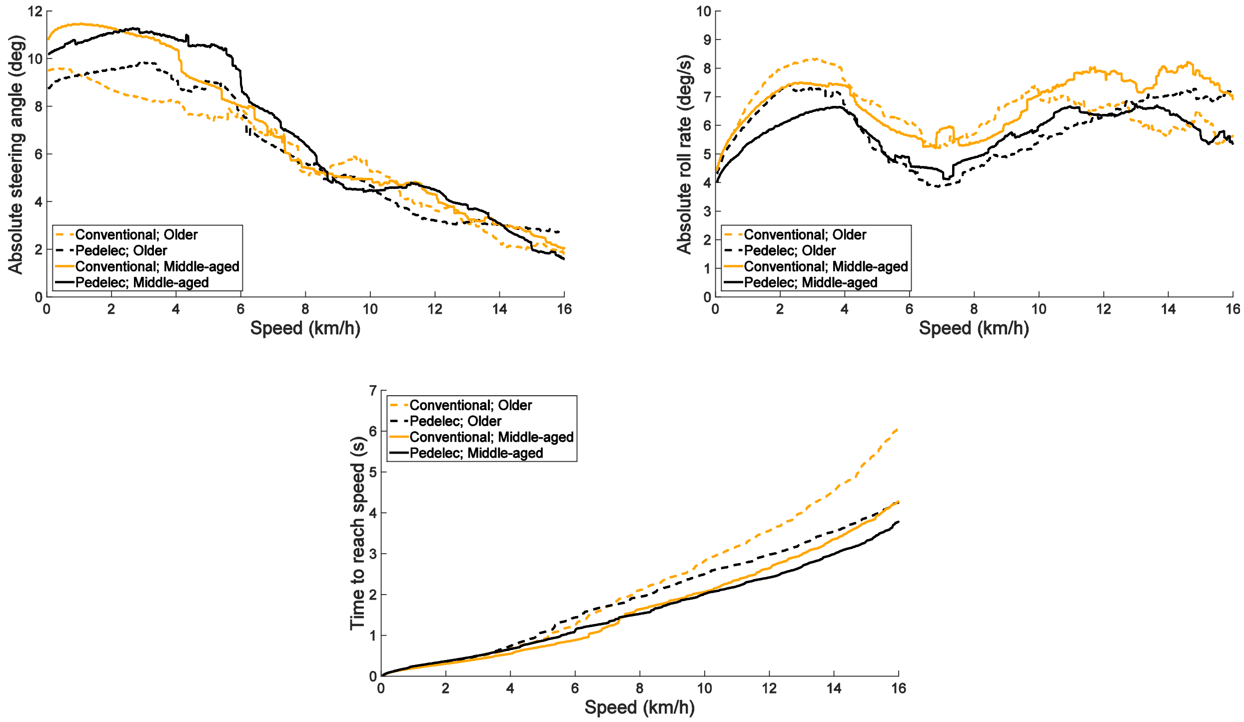

Fig. 4. Mean absolute steering angle (top left), mean absolute roll rate (top right), and mean time to reach threshold speed (bottom) during acceleration the task (Task 2). For improved clarity of the figures, the absolute steering angle and the absolute roll rate were filtered with an additional low-pass (1 Hz cut-off frequency) forward and reverse filter.

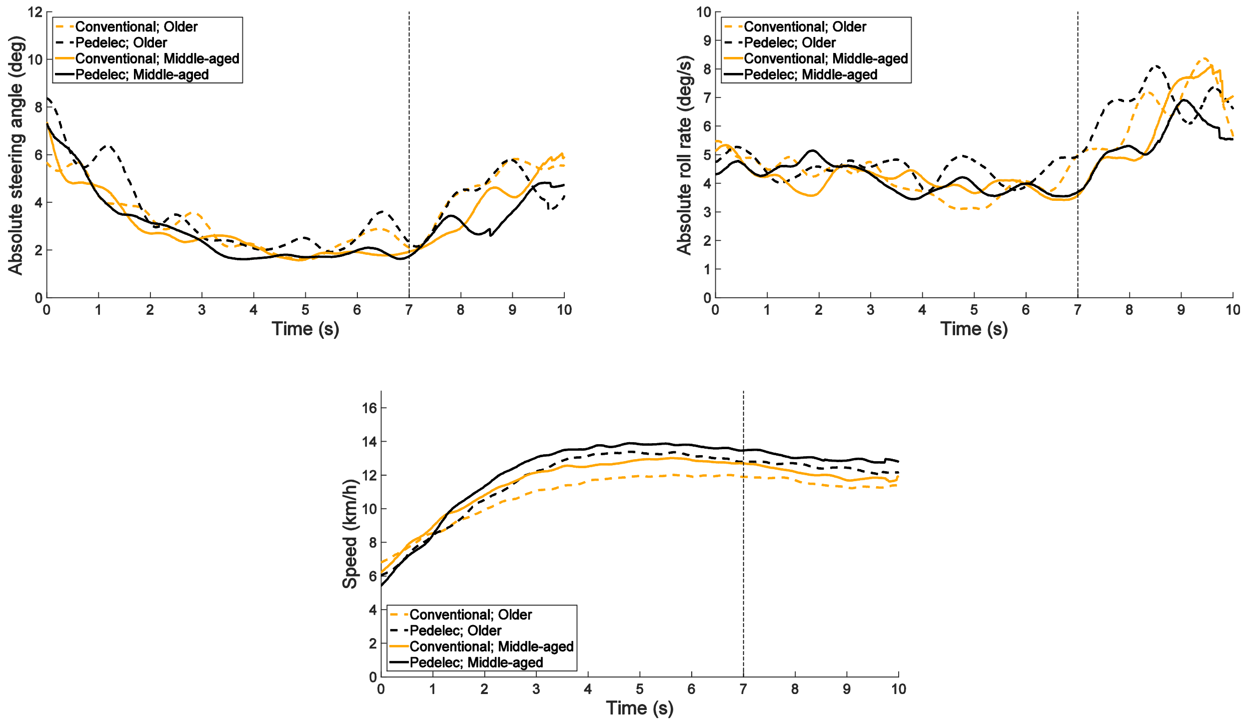

Fig. 5. Mean absolute steering angle (top left), mean absolute roll rate (top right), and mean speed (bottom) during the shoulder check task (Task 3). The moment when participants started to turn their head is indicated by the vertical dashed line. For improved clarity of the figures, the absolute steering angle and the absolute roll rate were filtered with an additional low-pass (1 Hz cut-off frequency) forward and reverse filter.

'3 s before head start – head start' and 'head start – head end', respectively) and on the mean absolute roll rate in the 'head start – head end' subtask ($t(50) = -2.802$, $p = 0.007$). Thus, older participants used more steering control than middle-aged participants when indicating direction by hand and performing the shoulder check (Table 5).

As can be seen in the top left of Figs. 3–5, the absolute steering angle on both bicycle types was high at the start of each exercise (i.e., when speed was low) and decreased with increasing speed/time. Another noteworthy observation was that both middle-aged and older cyclists showed large individual differences in steering performance (see *SD*s in Table 5).

3.3.2. Speed and time

As shown in Fig. 3 (bottom), cyclists slightly exceeded the instructed speed of 7 km/h in Task 1 on both bicycles during the whole task. The analysis of variance revealed a significant effect of bicycle type (means = 7.77 vs. 7.52 km/h for conventional bicycle and pedelec, respectively; $F(1,57) = 7.97$, $p = 0.007$), but the effect of age was not statistically significant. Interaction effects 'bicycle type × age' during Task 1 were not significant (Table 6).

Fig. 4 (bottom) clearly shows that when riding on the pedelec, participants accelerated faster compared to when riding on the conventional bicycle. Furthermore, middle-aged participants accelerated faster than older participants. Note that older participants on the pedelec reached the target speed after approximately the same number of seconds as middle-aged participants did on the conventional bicycle (means = 4.26 vs. 4.28 s, respectively). The analysis of variance showed a significant effect of bicycle type ($F(1,56) = 52.82$, $p < 0.001$) and age ($F(1,56) = 11.21$, $p = 0.001$), as well as an interaction between bicycle type and age ($F(1,56) = 17.41$, $p < 0.001$). This interaction effect indicates that older participants benefited more from using a pedelec than middle-aged participants in terms of accelerating as quickly as possible to 16 km/h (Fig. 4, bottom).

The analysis of speed in Task 3 showed there was a significant effect of bicycle type ($F(1,50) = 20.49$, $p < 0.001$; $F(1,50) = 11.01$, $p = 0.002$, for subtasks '3 s before head start – head start' and 'head start – head end', respectively). Participants rode faster on the pedelec than on the conventional bicycle while indicating direction by hand and shoulder check (Fig. 5, bottom). In addition to the analysis of speed in Task 3, the time when participants turned their head was examined, but no significant effect of bicycle type nor age was found. As in Task 1, interaction effects 'bicycle type × age' during Task 3 were not significant (Table 6).

3.4. Correlations between background variables, self-reported skills, and actual performance

As shown in Table 7, correlations between self-reported skills (measured by the CSI) and actual cycling performance were rather weak and out of 30 correlations, only two were statistically significant. Specifically, participants who had better safety

Table 7
Spearman rank-order correlations among all variables (performance measures were averaged across both types of bicycles).

		1	2	3	4	5	6	7	8
1	Gender (1 = female, 2 = male)	–							
2	Age (years)	0.11	–						
3	Kilometers per week	−0.02	−0.22	–					
4	Cycling frequency	−0.36**	−0.35**	0.55***	–				
5	Grip strength (N)	0.66***	−0.37**	0.10	−0.03	–			
6	Reaction time (ms)	−0.14	0.20	−0.22	0.02	−0.20	–		
7	CSI: Motor-tactical skills[a]	−0.20	−0.11	−0.14	0.10	−0.16	0.13	–	
8	CSI: Safety skills[a]	0.08	−0.22	−0.06	−0.03	0.17	−0.02	0.51***	–
9	T1: Mean absolute steering angle (deg) (5–20 s)	0.09	0.50***	−0.08	−0.14	−0.11	0.10	−0.17	−0.04
10	T1: Mean absolute roll rate (deg/s) (5–20 s)	0.18	0.53***	−0.24	−0.29*	−0.05	0.11	−0.11	−0.15
11	T1: Time delay between roll rate and steering rate (s)	−0.23	−0.34**	0.08	0.28*	−0.06	−0.01	0.25	0.27*
12	T1: R^2 between roll rate and steering rate (0–1)	0.40**	0.27*	−0.13	−0.17	0.28*	0.00	−0.21	−0.07
13	T2: Mean absolute steering angle (deg) (0–16 km/h)	−0.20	0.08	−0.25	−0.14	−0.08	0.15	0.25	0.05
14	T2: Mean absolute roll rate (deg/s) (0–16 km/h)	−0.28*	0.05	−0.05	0.03	−0.41**	−0.12	−0.16	−0.22
15	T3: Mean absolute steering angle (deg) (3 s before head start – head start)	0.10	0.53***	−0.21	−0.34*	−0.18	0.32*	−0.11	−0.15
16	T3: Mean absolute roll rate (deg/s) (3 s before head start – head start)	0.02	0.29*	0.06	−0.08	−0.11	0.24	−0.17	−0.09
17	T3: Mean absolute steering angle (deg) (head start – head end)	0.10	0.38**	−0.34*	−0.25	0.00	0.29*	−0.12	−0.08
18	T3: Mean absolute roll rate (deg/s) (head start – head end)	0.13	0.33*	−0.11	−0.06	0.00	0.16	−0.22	−0.18
19	T1: Mean speed (km/h) (5–20 s)	0.02	0.20	0.00	−0.05	−0.03	0.00	−0.02	−0.08
20	T3: Mean speed (km/h) (3 s before head start – head start)	0.04	−0.20	0.11	0.11	0.09	−0.16	−0.06	0.01
21	T3: Mean speed (km/h) (head start – head end)	−0.01	−0.17	0.23	0.19	−0.02	−0.11	−0.06	−0.04
22	T2: Time to reach 16 km/h (s)	−0.46***	0.37**	−0.11	0.01	−0.65***	0.37**	0.15	−0.27**
23	T3: Time head start – head end (s)	0.27	0.38**	−0.38**	−0.27	0.11	0.14	0.12	0.14

Notes. CSI – Cycling Skill Inventory, T1 – Task 1: Low-speed cycling, T2 – Task 2: Accelerating, T3 – Task 3: Shoulder check. Sample size varied between 51 and 61 for the 140 pairs of variables listed.

[a] Participants rated each item from 1 (*much better*) to 5 (*much worse*).

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

skills scores accelerated more slowly to the target speed of 16 km/h in Task 2 and had a shorter delay between roll rate and steering rate.

The correlation analysis also showed that high grip strength was positively related to (1) being male, (2) being young, and (3) a shorter time to reach the threshold speed of 16 km/h in Task 2. Reaction time positively correlated with total time in Task 2. Furthermore, females took longer to reach the target speed of 16 km/h in Task 2. Age was positively correlated with the mean absolute steering angle and mean absolute roll rate in Tasks 1 and 3, time measures in Tasks 2 and 3, and negatively with the time delay between roll rate and steering rate. Weekly distance traveled was inversely related to mean absolute steering angle when participants were looking over shoulder in Task 3 and also to the total time of this subtask (i.e., head start – head end). This suggests that more experienced participants performed the shoulder check subtask in shorter time and with lower mean steering angles.

4. Discussion

With the increasing use of new vehicle technologies such as pedelecs, it is imperative to determine how the vehicle technologies themselves and the characteristics of their users contribute to traffic safety. The popularity of pedelecs – particularly among older people who are considered as the most vulnerable group of road users due to their physical frailty (OECD, 2001) – led us to examine how age is associated with self-reported cycling skills and actual cycling performance.

Overall, the results of the low-speed cycling and shoulder check tasks showed that older cyclists maintain balance by additional steer and roll motions. On the contrary, no statistically significant differences in balancing the bicycles between two age groups were found while accelerating as fast as possible to a typical cruising speed.

It is interesting that older riders exhibited higher R^2 values and shorter time delays between roll rate and steering rate compared to middle-aged riders during low-speed cycling (Task 1). Similar results were found by Cain (2013) when comparing experienced and inexperienced cyclists. Specifically, in one of his experiments, Cain (2013) found that the R^2s between bicycle roll rate and steer rate were lower for cyclists than for non-cyclists. As mentioned previously, riders stabilize a bicycle by means of two main control inputs: steering and upper-body lean (Kooijman & Schwab, 2013). In addition, external perturbations such as crosswind can have a substantial effect on the dynamics of the bicycle (Schwab, Dialynas, & Happee, 2016). Thus, the determinants of the relationship between roll rate and steering rate are complex. We believe it is possible that riders of different experience and age groups adopted a different posture and different types of upper-body movements while cycling, giving rise to the observed differences in the time delay and R^2 measures.

The older cyclists experienced difficulties at the operational level, when indicating direction with the left hand and when looking over the shoulder (Task 3). As mentioned above, the 23 cyclists (out of the 31 older participants) who were included in statistical analysis performed significantly more corrections per time unit to stabilize a bicycle than middle-aged participants. Older cyclists may benefit from technology fitted on the bicycle that makes the head-turn task easier for them (see Engbers et al., 2014, for a recently developed technical solution: a rear-view assistant).

Consistent with previous research (e.g., Kallman et al., 1990; Shaffer & Harrison, 2007), older participants had a lower grip strength and longer reaction times than middle-aged participants. The results also showed a negative relationship between grip strength and the time to reach 16 km/h. Moreover, we found a positive association between reaction time versus the time to reach the threshold speed (Task 2) and the mean absolute steering angle during performing the shoulder check (Task 3). In other words, a reaction time measurement obtained in stationary non-cycling conditions was predictive of several measures of cycling performance. However, it should be noted that grip strength and reaction time are not necessarily specific causal factors of cycling skill, but are also manifestations of general age-related physical and cognitive fitness (e.g., Der & Deary, 2006). It is useful to point out that several previous studies have used a different approach, whereby reaction times were measured during cycling, either using a visual detection task (Vlakveld et al., 2015) or an auditory detection task (Wierda & Brookhuis, 1991). These studies have found that both very young cyclists (6–8 years; Wierda & Brookhuis, 1991) and older cyclists (65 or older; Vlakveld et al., 2015) have higher reaction times than middle-aged cyclists, pointing to a reduced spare mental capacity while cycling (Vlakveld et al., 2015; Wierda & Brookhuis, 1991).

Our field experiment confirms earlier research (Cain, 2013; Kooijman & Schwab, 2013) that the mean absolute steering angle was substantially higher at the start than after approximately first 5 s of the ride. These findings may have implications for the design of cycle lanes. For instance at intersections where cyclists usually have to stop and start, the lane width may have to be larger in comparison to straight sections when a high speed can be maintained (see Godthelp & Wouters, 1980 for further discussion).

The recorded data shown in Figs. 3 and 4 (top right) suggest that roll angle rates while cycling at low speed (Task 1) and accelerating (Task 2) were lower for the pedelec than for the conventional bicycle. This can be explained by pedaling which is performed with greater physical exertion on the conventional bicycle. This tentative explanation can be used as a basis for future research to more clearly demonstrate the interaction between bicycle types, pedaling, and roll motion.

The second research question in this study examined whether participants on a pedelec adopt different speeds than the same participants on a conventional bicycle. When participants cycled at their own pace (Task 3), they adopted a higher speed on the pedelec than on the conventional bicycle, which is consistent with previous research (Dozza et al., 2016; Schleinitz et al., in press; Vlakveld et al., 2015). Moreover, when instructed to accelerate as quickly as possible (Task 2), participants reached the 16 km/h threshold speed sooner on the pedelec than on the conventional bicycle, an effect that was most pronounced among the older cyclists. A comparison of the accelerations on the parking lot with accelerations from standstill at traffic lights (during the 30-min rides that took place before the present parking lot exercises) showed that whereas there was a significant effect of bicycle type up to 6 km/h on the parking lot, the effect was not significant at the traffic lights (Platteel et al., 2015). When accelerating up to 10 km/h (data analyzed between 6 and 10 km/h) participants gained the threshold speed more quickly on the pedelec than on the conventional bicycle regardless of the traffic context. The emerging conclusion here appears to be that cyclists *can* reach the desired speed faster on the pedelec, but in actual traffic cyclists benefit from the assistance provided by the electric motor to accelerate with less physical exertion rather than to accelerate faster (see also Schleinitz et al., in press).

An interesting finding was that older participants on the pedelec reached the threshold speed in approximately the same amount of time as middle-aged participants did on the conventional bicycle. Furthermore, the average speed of older people on the pedelec was approximately the same as the speed of the middle-aged cyclists on the conventional bicycle during the shoulder check. These results are in line with those obtained during the 30-min rides ridden on both bicycles before parking lot exercises (Vlakveld et al., 2015) and with the German Naturalistic Cycling Study (Schleinitz et al., in press) in which the low speed among older participants was interpreted as a compensation for reduced functioning (i.e., cyclists reduce their speed in situations involving high physical or mental demands; see also Fuller, 2005).

Consistent with literature on car driving, participants on average rated themselves to be better than an average cyclist of the same age. Specifically, across all 17 items of the CSI, in 45.7% of the cases participants rated themselves "better" or "much better" than the average cyclist, while only 4.5% rated themselves as "worse" and "much worse". Such a finding is commonly regarded as an illusion, because (if participants are representative of the population) it is extremely unlikely that most of drivers or riders are truly more skilled that the average driver/rider (Taylor & Brown, 1988). For methodological issues and explanations referring to distortions in social judgements and cognitive illusions which provide possible explanations for these findings, see Sundström (2008).

The third research question examined participants' own assessment of motor-tactical and safety skills and its correlation with actual cycling performance. Correlations between self-reported skills (measured by the CSI) and actual performance were weak and mostly not statistically significant. In addition to imprecisions of self-assessments, a possible explanation for the fairly low association between the questionnaire responses and actual cycling measures is that the CSI included a variety of skills (i.e., motor skills, perceptual skills, emotional skills, safety skills) whereas during the exercises on the parking lot the focus was on motor skills.

The fourth research question investigated whether participants believe their performance during field test was better on the conventional bicycle than on the pedelec, or vice versa. Participants believed that they could accelerate from standstill better on the pedelec than on the conventional bicycle, which concurs with the results of Task 2. In general, participants did not perceive large difference in control and maneuvering between the two bicycle types.

Several limitations should be considered when interpreting the results of the present study. First, self-selection bias should be kept in mind when interpreting the results. The cyclists voluntary participating in this study may have been more fit than an average older person. Thus, this study may have under-sampled the very old participants who are unable to ride a conventional bicycle. The average daily distance cycled by our participants was two to three times higher than the distance cycled by the average Dutch person (see CBS, 2015), which can be explained by the fact that only people who cycled regularly participated in our experiment. Second, all tasks were performed in a safe environment without other road users. As we discussed, cyclists may perform differently when conducting exercises on a parking lot compared to when riding in actual traffic (see Platteel et al., 2015). Third, despite the use of high quality sensors, we did not compare the bicycles on steer and roll rate measures by means of statistical tests because of small differences in the accuracy of these sensors. Consequently, the results do not provide a comprehensive insight into how the greater mass of a pedelec and available cycling power affects the cyclist's performance. Although we have no reason to suppose that any systematic bias exists in the present results, it is possible that small differences in calibration, play, or mounting of the sensors distort the results, especially when considering that high-frequency vibrations are omnipresent in cycling data. Note that this limitation only concerns comparisons *between* bicycles; the assessment of effects *within* bicycles (i.e., age effects, correlations with self-reports) is not susceptible to this problem. Fourth, the research design of this study does not permit drawing conclusions on whether cyclists overestimate or underestimate themselves. Future research can shed more light on this topic by relating cyclists' self-assessment to reference values in standardized cycling exercises and an examiner's assessment.

5. Conclusions

The results of the present study showed that cyclists aged 65 and over maintained balance by additional steer and roll motions during low-speed cycling at 7 km/h and looking over the shoulder, as compared to middle-aged cyclists. Moreover, our results showed that pedelecs allowed older cyclists in particular to accelerate quickly to cruising speed. Consistent with literature on car driving, cyclists rated themselves to be better than average cyclists of the same age. Additionally, self-reported motor-tactical and safety skills were not strongly associated with measures of actual cycling performance. The age-related differences in cycling performance may have to be taken into account when designing interventions to support cycling safety. However, the challenge remains to determine whether a pedelec affects the risk of crashing as compared to conventional bicycles, and whether any increase in bicycle crashes should be attributed to population aging and/or to the bicycle characteristics. Future field studies are needed in the actual traffic environment to investigate how task demands at the tactical level (i.e., traffic situations) influence the task execution at the operational level (e.g., keeping balance, accelerating).

Acknowledgements

This study was facilitated by the Dutch Ministry of Infrastructure and Environment and has been supported in part by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/under REA grant agreement n° 608092. An abstract of this work has been submitted to the International Conference on Traffic and Transport Psychology, 2–5 August, 2016, Brisbane, Australia. The authors wish to thank Willem Vlakveld and Marjolein Boele for their efforts in setting up and conducting the experiment, Jolieke de Groot–Mesken for sharing the data from the CSI, Jodi Kooijman, Thom van Beek, and Nick Appelman for designing and building the instrumented bicycles, and Gordon Lovegrove for his valuable comments on the manuscript.

References

Cain, S. M. (2013). *An experimental investigation of human/bicycle dynamics and rider skill in children and adults.* Doctoral dissertation. Ann Arbor, MI: University of Michigan.
CBS (2015). *The Netherlands: Cycling country (Factsheet)*. The Hague: CBS Statistics Netherlands.
Conway, J. M., & Huffcutt, A. I. (2003). A review and evaluation of exploratory factor analysis practices in organizational research. *Organizational Research Methods, 6*, 147–168.
Daniels, E. B., Zajkowski, M. M., & Drury, C. G. (1976). Bicycle riding performance. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 20, pp. 410–414). MD, USA: College Park.
De Groot-Mesken, J., & Commandeur, J. (2014). *Hoe goed weten oudere fietsers wat ze kunnen? Een veldexperiment met gewone en elektrische fietsen* [How capable are elderly cyclists of assessing their skills? A field experiment with conventional and electric bicycles] (Report No. R-2014-19). The Hague: SWOV Institute for Road Safety Research.
De Winter, J. C. F., & Dodou, D. (2012). Factor recovery by principal axis factoring and maximum likelihood factor analysis as a function of factor pattern and sample size. *Journal of Applied Statistics, 39*, 695–710.
Der, G., & Deary, I. J. (2006). Age and sex differences in reaction time in adulthood: Results from the United Kingdom health and lifestyle survey. *Psychology and Aging, 21*, 62–73.
Dodds, R. M., Syddall, H. E., Cooper, R., Benzeval, M., Deary, I. J., Dennison, E. M., ... Kirkwood, T. B. (2014). Grip strength across the life course: Normative data from twelve British studies. *PLOS ONE, 9*, e113637.
Dozza, M., Bianchi Piccinini, G. F., & Werneke, J. (2016). Using naturalistic data to assess e-cyclist behavior. *Transportation Research Part F: Traffic Psychology and Behaviour, 41*, 217–226.
Drury, C. G., & Daniels, E. B. (1980). Predicting bicycle riding performance under controlled conditions. *Journal of Safety Research, 12*, 86–95.
Elander, J., West, R., & French, D. (1993). Behavioral correlates of individual differences in road-traffic crash risk: An examination of methods and findings. *Psychological Bulletin, 113*, 279–294.
Engbers, C., Dubbeldam, R., Schaake, L., De Hair, S., De Goede, M., & Buurke, J. (2014). Supporting elderly cyclist with rear-view assistance. In *Proceedings of the international cycling safety conference 2014*, Gothenburg, Sweden.
Fonda, B., Sarabon, N., & Li, F.-X. (2016). Bicycle rider control skills: Expertise and assessment. *Journal of Sports Sciences* (in press).
Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis & Prevention, 37*, 461–472.
Fyhri, A., & Fearnley, N. (2015). Effects of e-bikes on bicycle use and mode share. *Transportation Research Part D: Transport and Environment, 36*, 45–52.
GDV (2014). *Compact accident research: Traffic safety of electric bicycles (No. 46)*. Berlin: GDV German Insurance Association.
Godthelp, J., & Wouters, P. I. J. (1980). Course holding by cyclists and moped riders. *Applied Ergonomics, 11*, 227–235.
Horrey, W. J., Lesch, M. F., Mitsopoulos-Rubens, E., & Lee, J. D. (2015). Calibration of skill and judgment in driving: Development of a conceptual framework and the implications for road safety. *Accident Analysis & Prevention, 76*, 25–33.
Jensen, A. R. (2006). *Clocking the mind: Mental chronometry and individual differences*. Amsterdam: Elsevier.
Kallman, D. A., Plato, C. C., & Tobin, J. D. (1990). The role of muscle loss in the age-related decline of grip strength: Cross-sectional and longitudinal perspectives. *Journal of Gerontology, 45*, M82–M88.
Keskinen, E., & Hernetkoski, K. (2011). Driver education and training. In B. E. Porter (Ed.), *Handbook of traffic psychology* (pp. 403–422). London: Academic Press.
Kooijman, J. D. G., Schwab, A. L., & Moore, J. K. (2009). Some observations on human control of a bicycle. In *Proceedings of the ASME 2009 international design engineering technical conferences & computers and information in engineering conference* (pp. 2021–2028), San Diego, CA, USA.
Kooijman, J. D. G., & Schwab, A. L. (2013). A review on bicycle and motorcycle rider control with a perspective on handling qualities. *Vehicle System Dynamics, 51*, 1722–1764.
Kuiken, M., & Twisk, D. (2001). *Safe driving and the training of calibration* (Report No. R-2001-29). Leidschendam: SWOV Institute for Road Safety Research.
Lajunen, T., & Summala, H. (1995). Driving experience, personality, and skill and safety-motive dimensions in drivers' self-assessments. *Personality and Individual Differences, 19*, 307–318.
MacArthur, J., & Kobel, N. (2015). Regulations of e-bikes in the United States: A policy review. In *Transportation research board 94th annual meeting*, Washington DC, USA, No. 15-4235.
Michon, J. A. (1985). A critical view of driver behavior models: What do we know, what should we do? In L. Evans & R. C. Schwing (Eds.), *Human behavior and traffic safety* (pp. 485–524). New York: Plenum Press.
Moore, J. K., Kooijman, J. D. G., Schwab, A. L., & Hubbard, M. (2011). Rider motion identification during normal bicycling by means of principal component analysis. *Multibody System Dynamics, 25*, 225–244.
Mortimer, R. G., Domas, P. A., & Dewar, R. E. (1976). The relationship of bicycle manoeuvrability to handlebar configuration. *Applied Ergonomics, 7*, 213–219.
OECD (2001). *Ageing and transport: Mobility needs and safety issues*. Paris: OECD Publishing.
OECD/International Transport Forum (2013). *Cycling, health and safety*. Paris: OECD Publishing/ITF.
Papoutsi, S., Martinolli, L., Braun, C. T., & Exadaktylos, A. K. (2014). E-bike injuries: Experience from an urban emergency department – A retrospective study from Switzerland (Article ID 850236). *Emergency Medicine International*.
Platteel, S., Twisk, D., & Lovegrove, G. (2015). Pedelec and instability of the elderly during mounting manoeuvres. In *Proceedings of the 4th International Cycling Safety Conference*. Germany: Hannover.
Rice, R. S., & Roland, R. D. (1970). *An evaluation of the performance and handling qualities of bicycles* (Technical Report VJ-2888-K). Buffalo, NY: Cornell Aeronautical Laboratory.
Schepers, J. P., Fishman, E., Den Hertog, P., Klein Wolt, K., & Schwab, A. L. (2014). The safety of electrically assisted bicycles compared to classic bicycles. *Accident Analysis & Prevention, 73*, 174–180.

Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J., & Gehlert, T. (2016). The German naturalistic cycling study – Comparing cycling speed of riders of different e-bikes and conventional bicycles. *Safety Science* (in press).

Schwab, A. L., Kooijman, J. D. G., & Meijaard, J. P. (2008). Some recent developments in bicycle dynamics and control. In *Proceedings of the fourth european conference on structural control (4ECSC)*, St. Petersburg, Russia.

Schwab, A. L., Dialynas, G., & Happee, R. (2016). The effect of crosswind on the dynamics and control of bicycle. In *Proceedings of the 4th joint international conference on multibody system dynamics*, Montréal, Canada.

Shaffer, S. W., & Harrison, A. L. (2007). Aging of the somatosensory system: A translational perspective. *Physical Therapy, 87*, 193–207.

Sundström, A. (2008). Self-assessment of driving skill – a review from a measurement perspective. *Transportation Research Part F: Traffic Psychology and Behaviour, 11*, 1–9.

SWOV (2013). *Cyclists (SWOV Fact sheet)*. Leidschendam: SWOV Institute for Road Safety Research.

Taylor, S. E., & Brown, J. D. (1988). Illusion and well-being: A social psychological perspective on mental health. *Psychological Bulletin, 103*, 193–210.

Van Boggelen, O., Van Oijen, J., & Lankhuijzen, R. (2013). *Feiten over de elektrische fiets [Facts about the electrically assisted bicycle]*. Utrecht: Fietsberaad.

Vlakveld, W. P., Twisk, D., Christoph, M., Boele, M., Sikkema, R., Remya, R., & Schwab, A. L. (2015). Speed choice and mental workload of elderly cyclists on e-bikes in simple and complex traffic situations: A field experiment. *Accident Analysis & Prevention, 74*, 97–106.

Weber, T., Scaramuzza, G., & Schmitt, K.-U. (2014). Evaluation of e-bike accidents in Switzerland. *Accident Analysis & Prevention, 73*, 47–52.

Wierda, M., & Brookhuis, K. A. (1991). Analysis of cycling skill: A cognitive approach. *Applied Cognitive Psychology, 5*, 113–122.

Wolf, A., & Seebauer, S. (2014). Technology adoption of electric bicycles: A survey among early adopters. *Transportation Research Part A: Policy and Practice, 69*, 196–211.