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The different ways to get on and off a bicycle for young and old

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ABSTRACT

In the Netherlands, each year 12,000 older cyclists require medical attention due to a single-bicycle accident where no other party is directly involved. Most of these accidents occur at low cycling velocities and 20% occur during (dis)mounting the bicycle. Little is known about the strategies and corresponding kinematics of (dis)mounting. This study aims to classify (dis)mounting strategies of young and older cyclists and assess corresponding kinematics.

Thirteen young (18–40 years) and 33 older (65–90 years) cyclists, 13 with and 20 without a bi-cycle fall-history, participated. They were asked to mount the bicycle, cycle normally, stop and wait, continue cycling and dismount the bicycle at a certain point. Bicycle and cyclist motions were recorded with 10 Inertial Measurement Units and 2 video cameras. Kinematic parameters during the (dis)mounting period were assessed. First, a qualitative analysis of the different methods of (dis)mounting and 'waiting' was made from the videos. Second, a quantitative assessment of the relationships between age, fall-history, gender and the kinematic parameters during (dis)mounting and waiting were studied.

We identified 2 mounting, 3 dismounting and 2 waiting categories, which each consisted of 2 or 3 sub-types based on timing to get on or off saddle and swing leg through frame or over saddle. The categories can mainly be distinguished by the first foot that is lifted on or off the pedal. Older cyclists and females prefer other strategies compared to young cyclists and males, respectively. E.g. during mounting, 70% of the young cyclists lift their inside foot, the foot closest to the bicycle, and place it on the pedal, while 80% of the older cyclists lift their outside foot and put it on the pedal and start pushing off with their inside foot from the ground one or more times. Furthermore, bicycle and cyclist kinematics could be related to age, fall-history and gender. Higher thigh angular velocities and accelerations (around mediolateral axis) were found for older cyclists and females compared to young cyclists and males, respectively. These differences, among others, may explain the high injury risk for older cyclists and females in single-bicycle accidents.

1. Introduction

The Dutch use cycling on a daily basis as the main means of short distance transport. Older adults, aged 65 years and older, cycle as much as younger adults, though the reason for transportation may be different. During the last decade our older population has increased in number and also their cycling has increased (Consumer Safety Institute, 2011; Statistics Netherlands, 2007). Unfortunately, also the number of older cyclists admitted to hospitals after a bicycle accident has increased with 40%: each year 18,000 cyclists aged 55 years and older require first aid medical attention or hospital admission (Consumer Safety Institute, 2011, 2010). Accident analysis in the Netherlands has shown that three-quarters of these reported accidents are single bicycle crashes, an accident where no other road user is directly involved (Consumer Safety Institute, 2011). Furthermore, the relative risk of sustaining an injury due to a single bicycle crash is 2–5 times higher for cyclists aged 65 years and older compared to other adults (Berveling and Derriks, 2012). The high injury risk in single bicycle crashes, and especially for older cyclists is not a Dutch phenomenon alone. In a review, Schepers and international colleagues report similar findings in single bicycle crash frequencies from all over the world (Schepers et al., 2014a). Also the increased injury risk for older cyclists has been pointed out (Niska et al., 2013;

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Rodgers, 1995). Awareness has grown for this vulnerable cycling group for whom cycling is an important means of transportation, social interaction and health (Berveling and Derriks, 2012; Ministry of Infrastructure and Environment, 2012).

In-depth accident analyses have been performed to attain better insight in accident causes and mechanisms of single bicycle crashes in order to develop countermeasures. Accident causes may be infra-structure related such as collision with an obstacle or road quality, or cyclist related (Consumer Safety Institute, 2010; Niska et al., 2013; Kruijer et al., 2013; Schepers and Klein-Wolt, 2012; Davidse et al., 2013; Hagemeister and Tegen-Klebingat, 2013; Reynolds et al., 2009; Scheiman et al., 2010). Cyclist related factors include, among others, cyclist distraction and loss of control at low cycling velocities, due to steering or braking manoeuvres. Of the older cyclists that require medical attention after a single bicycle crash, 22% fell during (dis)mounting their bicycle compared to 8% for the other adults (Niska et al., 2013; Scheiman et al., 2010). No external factors such as bicycle type or baggage carriage could be related to this higher fall risk during (dis)mounting for older cyclists compared to younger cyclists (Schepers and Klein-Wolt, 2012). Furthermore, Kruijer et al. (2013) reported more single bicycle accidents occurred during dismounting (13%) compared to mounting (9%) among older cyclists who were questioned after being admitted to emergency treatment ($N = 245$). Schepers and Klein-Wolt (2012) suggested that physical abilities and the (dis)mounting method may play a role. Hagemeister and Tegen-Klebingat (2013) confirm that physical ability is related to (dis)mounting problems, but not to fall-history. So far, little is known about (dis)mounting methods, the difference between mounting and dismounting, and the relationships between physical abilities, (dis)mounting methods and fall risk. A better understanding of the (dis)mounting methods and corresponding bicycle and cyclist kinematics could be used as starting point in future accident risk studies.

This observational study aims to classify the different ways older and younger cyclists use to mount or dismount a bicycle by means of a qualitative description of body part movements. Secondly, we aimed to explore the relationships between age, gender and fall-history and (dis)mounting kinematics to attain insight in possible fall risks. Finally, mounting kinematics were compared to dismounting kinematics.

2. Methods

2.1. Participants

This observational study was part of a larger study during which cycling behaviour of young and older cyclists was assessed while performing various cycling tasks. The participants were recruited through an advertisement in the local newspaper or by means of flyers at local meeting points. Inclusion criteria for the study were: younger participants aged between 18 and 40 years and older participants aged 65 years or 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. Bicycle fall-history was registered and was defined as a single bicycle crash within the last 2 years.

Fifteen healthy young and 33 older cyclists participated in this study after signing an informed consent. A physiotherapist was always present and extra supporting staff was present for those cyclists with high fall risk (self-reported fall-history) or unsafe cycling behaviour. Unsafe cycling behaviour could be observed during the phase of getting acquainted with the bicycle and included difficulties (dis)mounting the bicycle in terms of balance disturbances while standing on one leg or problems lifting foot over the frame, difficulties cycling off in terms of slow acceleration and a lot of sway. This study was approved by the Medical Ethical Committee Twente, Enschede, The Netherlands. The following demographic data were recorded: gender, age, body weight, height, self-reported medication usage and degenerative diseases, and fall-history.

2.2. Test protocol

The cycling tests were performed outside on a large parking lot with no other road users interfering. The participants were asked to perform the following activities in a self-selected way: stand next to the bicycle, mount the bicycle, cycle for 200 m at self-selected comfortable velocity, break, dismount and come to a halt next to the bicycle. The participants were also asked to stand next to the bicycle, mount the bicycle in a self-selected way, cycle for about 400 m at a comfortable velocity, break and wait at predefined stopping point, continue cycling when indicated for about 400 m, break, dismount and come to a standing posture next to the bicycle. From the first described test trials the mounting and dismounting tasks were analysed, from the second described test trials the waiting task (including dismounting and re-mounting) was analysed. Each test trial was repeated thus 2 (dis)mounting and waiting tasks were available for analysis. Cycling test preparation took about 30 min. The described cycling tests were part of a more extensive test protocol which took about 1–1.5 h. When tired, the cyclists could take a rest in between the different cycling trials. The participants were able to retreat from the tests at any stage.

2.3. Measurement system

3D cycling movement data was recorded from wireless 3D inertial movement sensors (MTw-38A70G20 Xsens, Enschede, The Netherlands) with the FusionTools software (Roessingh Research and Development, Enschede, The Netherlands) built around the Xsens sensor SDK MT 3.81. One sensor was attached to the frame and one sensor was attached to the handle bar of the bicycle to assess the bicycle kinematics. To measure the movement of the cyclist, a total of 8 sensors were attached to the following body segments: left foot, right foot, left shank, right shank, left thigh, right thigh, pelvis and sternum (Fig. 1). All sensors were attached to the bicycle and cyclist by means of easy click-on click-off holding straps (Xsens standard wireless elastic strap set).

Prior to the tests, a 'segment calibration' procedure was performed to facilitate translation of the sensor orientation data (orientation of sensor casing in global inertial world frame aligned with magnetic north) into body segment orientation data (orientation of body segment or bicycle segment in a global inertial world frame aligned with cycle track direction). This also facilitated translation of sensor casing acceleration and angular velocity data into body segment acceleration and angular velocity. Subsequently joint kinematics were defined as 'child' segment kinematics relative to 'parent' kinematics and estimated (E.g. 'joint' knee data equals 'child segment' shank data in global frame relative to parent segment 'thigh' data in same global frame). The calibration procedure of the bicycle included controlled lifting of the bicycle front wheel around the bicycle 'left to right' axis and controlled rolling around the bicycle's long axis to define the bicycle frame segment; and controlled rotation of the steer around its steer axis. For the body segment calibration, the participants performed controlled squats and heel rises around their medio-lateral axis (Baten et al., 2004). A rotational segment orientation axes error of less than 1° was obtained after repeated bicycle frame calibration. Calibration errors in limb segment orientation axes may lead to

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Fig. 1. Attachment of the sensors on the test bicycle and cyclist.

absolute measurement errors between repeated measurement sessions of 3–5°. Therefore, only relative angles with respect to initial position will be assessed for body segments. The sensor measurement data were wirelessly transmitted to, and recorded with, a tablet pc positioned in a case on the bicycle luggage carrier (ACER w510 KD1, Windows 8). Two video cameras were used to visually record the mounting, dismounting and waiting tasks from a rear view, front view and side view (HERO2, GoPro, Inc., USA). A standard female bicycle was used in all tests: a TREK L300 BLX low with 50 cm frame height, suitable for smaller and larger cyclists between 155 cm and 185 cm (Fig. 1).

2.4. Analysis of the (dis)mounting categories

The recordings from the two video cameras were used to qualify the different ways the young and older cyclists used for the mounting, the dismounting and the waiting tasks during the cycling test trials. For each task the movements of the inside foot (i.e. the foot closest to the bicycle), outside foot, pelvis and bicycle and corresponding chronologic order were described in detail and generalised where possible (for definitions see Fig. 2). Description items included for example inside foot on contra-lateral pedal, inside foot through frame, outside foot on ground, bicycle comes to halt, gaining speed, braking, sitting down or off saddle. From these descriptions, different methods were identified and grouped into different categories. We used the categories to classify the strategy to mount, dismount and wait.

2.5. Analysis of the bicycle and cyclist kinematics

From the raw sensor data, all 3-dimensional body and bicycle segment kinematics were estimated using FusionTools, an in-house developed software program in LabVIEW (National Instruments) and the Xsens Mtw SDK 3.8.1 sensors. Post-processing of the kinematic data was done in MATLAB (version R2013b, MathWorks). All kinematic data were filtered with a second order low-pass Butterworth filter of 15 Hz. In this study, we only analysed kinematics during getting on and off the bicycle. Therefore, a mounting and dismounting phase was defined during each cycling test trial. The mounting phase started when the knee angular velocity changed from zero deg/s when the first foot was lifted off the ground and ended when the cyclist was sitting on the saddle and both legs had reached a constant cycling frequency (harmonic cycling) as judged manually by the angular velocity of both knee joints. The dismounting started when the cycling frequency stopped being constant and ended when the angular velocity of both knees became zero and continued to be zero when the second foot was on the ground. For the waiting task, two phases were defined: first a dismounting phase was defined which was followed by a mounting phase. The corresponding cycling velocity was calculated by integrating the acceleration signal in forward direction of the bicycle frame sensor and using a second order low-pass Butterworth filter of 15 Hz. The calculation error over the whole cycling test trial (from mounting till dismounting) was limited to less than 0.02 m/s.

Fig. 2. Examples of used (dis)mounting body and bicycle part definitions.

The *(dis)mounting performance* of the participants was analysed by means of temporo-spatial and kinematic parameters. The total (dis)mounting time was assessed to identify the time spent in a more or less unstable cycling condition. Cycling velocity is a measure for the bicycle–cyclist system stability. The maximum values of the bicycle kinematics, steer, yaw and roll (Fig. 3) have been related to altered cycling behaviour and cycling velocity (Moore et al., 2011; Van den Ouden, 2011; Mori and Mizohata, 1995). The maximum thigh angular velocity and acceleration indicated the limb muscle power and force required during mounting or dismounting. The sternum angular velocity and acceleration may be involved in maintaining balance on the bicycle. In overview, the following parameters were analysed in this study:

- Total time of (dis)mounting phase.
- Cycling velocity at end of the mounting phase or beginning of dismounting phase and corresponding maximum acceleration.

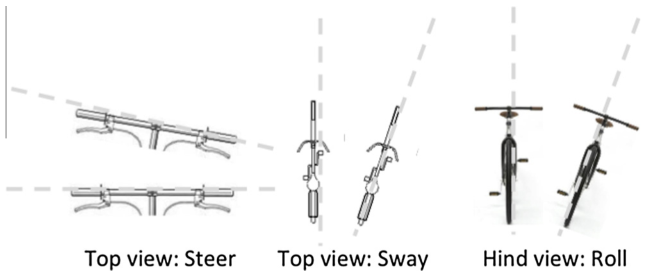

Fig. 3. Definitions of bicycle kinematics.

– Absolute maximum of bicycle roll angle, angular velocity, angular acceleration.
– Absolute maximum of bicycle yaw angle, angular velocity, angular acceleration.
– Absolute maximum of steer angle, angular velocity, angular acceleration.
– Absolute maximum of thigh flexion angle w.r.t. pelvis; maximum thigh angular velocity and corresponding acceleration of the local sensor calibrated medial–lateral rotation axis.
– Absolute maximum of sternum flexion angle w.r.t. pelvis; and maximum sternum angular velocity and corresponding acceleration of the local sensor calibrated anterior–posterior rotation axis.

2.6. Statistical analysis

The means and corresponding standard deviations (SD) of the demographic parameters were assessed and significant differences ($p < 0.05$) between the Young and Older age groups were assessed by means of an independent *t*-test. Future analysis was performed with three participant groups: Young ($N = 14$), Older with no fall-history ($N = 18$) and Older with fall-history ($N = 15$). Graphical representations of the distribution of the participants between (dis)-mounting categories were made. From these, it appeared that age group, fall-history and gender all influenced the choice of (dis)-mounting and waiting strategy. As there are no young participants in the fall-history group, we created 2 independent factors: 'Gender' (male, female) and 'Age-Risk' (Young, Older and Older with fall-history groups). Possible association between these independent categorical variables were studied by means of cross-tabulation. Subsequently, uni-variate analysis was performed to study the individual associations between the independent factors 'Gender' and 'Age-Risk' and each (dis)mounting categories by means of cross-tabulations. Associations with a significance level of $p < 0.10$ were thereafter entered into a (binary or multinominal) logistic regression model to assess the corresponding individual effects (by means of the odds ratios). For model evaluation the Likelihood Ratio test (Chi-square X^2 for model fit) and Nagelkerke pseudo *R* square (for explained variance) were assessed. The significant *p* values and corresponding odds ratio Exp(*B*) of the individual predictors for each (dis)mounting category were reported.

Descriptive statistics of all cycling parameters were performed and data were plotted as function of age, fall-history and gender. Data were tested for normal distribution by means of the Shapiro Wilk test. A Pearson correlation test was performed on the kinematic parameters for mounting and dismounting for each cycling task (normal and waiting). However, only limited consistent relationships could be identified between kinematic parameters for all cycling tasks. Furthermore, at present it is not clear which kinematic parameters is most representative for cycling performance in terms of balance. Therefore, each kinematic parameter was tested as dependent parameter separately. The relationships between the dependent (dis)mounting kinematic parameters and the independent factors gender, age and fall-history were explored by means of multi-variate linear regression models. Model fit (*R* square), *p*-values, the unstandardized reference value B_0 and corresponding factor confidence interval for *B* are presented. The statistical significant effects ($p < 0.05$) were not adjusted for multiple testing with 2 factors.

Finally, to test whether the assessed mounting and dismounting kinematics were comparable, a paired *t*-test was performed. Significant differences ($p < 0.000$) and corresponding mean values and mean differences are presented. Statistical analysis was performed in SPSS (Statistical Packages for Social Sciences, 20.0, SPSS Inc, Chicago, Illinois, USA).

3. Results

3.1. Participants

All participants were able to perform the (dis)mounting and waiting tasks in a self-selected manner. However, due to sensor data loss or missing of tasks, not all participants and tasks could be included in this analysis. Of the older participants, 2 cyclists required special attention during the cycling tests due to problems mounting or dismounting the bicycle: a physiotherapist would accompany the cyclist. The self-reported pathologies and corresponding medication usage by the older participants were representative for their age group and included, among others: degenerative osteoarthritis of knee, hand, shoulder and lower back joints, cardio-vascular impairments, Diabetes mellitus and osteoporosis. The younger participants reported the following medical issues: asthma, a painful knee and Vitamin B12 shortage. In Table 1 an overview can be found of the young and older participant characteristics, including the two older sub-groups. The Shapiro–Wilk test indicated that the major part of the demographic data was normally distributed and parametric statistical tests were used. By means of Independent samples *t*-tests, significant differences

Table 1
Demographic characteristics.

	Young ($N = 14$)		Older ($N = 33$)		Older No fall-history ($N = 18$)		Older Fall-history ($N = 15$)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age (years) *	26.0	3.7	74.6	6.3	73.9	5.6	75.5	7.0
Gender (male/female)	6 m 8 f		12 m 21 f		10 m 8 f		2 m 13 f	
Height (m)	1.78	0.07	1.71	0.10	1.72	0.10	1.69	0.10
BMI (kg/m^2) *	23.1	2.8	25.8	2.5	26.0	2.4	25.7	2.6
Participants with fall history *	0		15		0		15	

* Significant difference ($p < 0.05$) between age groups Young and Older.

were observed between young and older participants for all demographic parameters with exception of body height: the young cyclists had an average age of 26 (SD = 4) years and the older cyclists had an average age of 75 (SD = 6) years respectively; the older cyclists had a higher BMI (BMI = 26) than the young cyclists (BMI = 23); and furthermore, the older cyclist fall-history group consisted of 13 females and only 2 males, respectively. Therefore, in comparison to the young group, in ratio more females participated in the older group.

3.2. Mounting, dismounting and waiting methods

Different methods for the mounting, dismounting and waiting tasks were observed. For each task, several methods were grouped to obtain 2 or 3 main categories. The grouping was done based on similarities in lower limb activities, 'sitting down on' or 'lifting from' the saddle and the chronologic order in which such activities took place. Movement of the inside and an outside foot were described, with the inside foot being closest to the bicycle. Since each foot can be placed on each of the pedals, we defined an ipsilateral and contralateral pedal. Straathof (2014) reported a detailed description of the various methods. Table 2 gives an overview and characteristics of the different (dis)mounting categories.

Fig. 5 shows the observed distribution of the (dis)mounting strategies of the participants. We observed that 71% of the young group chose for mounting category 2, where the inside foot is lifted and placed on the contra-lateral pedal first (Fig. 4b). On the contrary, 78% of the older no fall-history group and 87% of the older fall-history group chose for mounting category 1, where the outside foot is lifted and placed on the pedal first (Fig. 4a). A similar trend was found for dismounting strategies: 84% of the young group chose for dismounting strategy 1, where the outside foot is lifted from pedal first; and 44% of the older no fall history group and 57% of the older fall-history group used dismounting category 2, where the inside foot is lifted of pedal first. For waiting strategy, 80% of the young group demonstrated waiting category 1, where the cyclist stays on the bicycle, while 73% of the older fall-history group mainly demonstrated waiting category 2, where they dismount and remount the bicycle.

Males and females used all (dis)mounting and waiting categories (Fig. 5b). However, females preferred mounting category 1 (outside foot on pedal first) and waiting category 2 (getting off and on the bicycle). Males preferred dismounting category 1 (outside foot off pedal) and waiting category 1 (staying on bicycle).

To analyse the relationships between Age-Risk and Gender to the (dis)mounting and waiting strategies, uni-variate and multi-variate analyses were performed. The univariate analysis (Cross-tabs) found following relationships: Age-Risk was related to mounting strategy (Fisher $X^2 = 11.8$, $p = 0.003$); Age_Risk (Fisher $X^2 = 14.2$, $p = 0.004$) and Gender (Fisher $X^2 = 8.0$, $p = 0.018$) were related to dismounting strategy; Age_Risk (Pearson $X^2 = 4.9$, $p = 0.106$) and Gender (Pearson $X^2 = 5.1$, $p = 0.042$) were related to Waiting strategy. These (almost) significant factors were then entered into the multi-variate regression analysis: The regression model fit for mounting strategy is moderate ($X^2 = 12.7$, $p = 0.002$ and R^2 Nagelkerke = 0.33). The results indicated that Age_Risk ($p = 0.004$, Exp(B) = 16.2) was related to mounting indicating that the chance an older cyclist (Age_Risk 1) demonstrates MC 2 is about 16 times higher compared to Young cyclists. For dismounting strategy, the regression model fit is almost good ($X^2 = 24.7$, $p < 0.000$ and R^2 Nagelkerke = 0.49). Both Age_Risk ($p = 0.005$, Exp(B) = 0.023) and to some extent Gender ($p = 0.10$, Exp(B) = 0.23) were related to the dismounting strategy: the males were about 4 times more inclined to demonstrate DC 1 compared to females, and the young cyclists had a 40 times higher chance of demonstrating DC 1 compared to the Older group. The model fit for Waiting strategy with both Age_Risk and Gender as factors was low ($X^2 = 8.7$, $p = 0.033$ and R^2 Nagelkerke = 0.27). No significant relations could be found for the Waiting strategy, though gender ($p = 0.078$, Exp(B) = 4.2) may play a role. When entering the factor Gender alone into the regression model, the factor became significant ($X^2 = 5.3$, $p = 0.023$ and R^2 Nagelkerke = 0.17), predicting 5

Table 2
Characteristics of the different mounting, dismounting and waiting categories. Each category consists of 2–4 methods as indicated with the || or || and || and/or ||.

<table>
<tr><th>Mounting category 1</th><th>Mounting category 2</th></tr>
<tr><td>Outside foot on ipsilateral pedal</td><td>Inside foot through the frame || or || inside leg swings over saddle</td></tr>
<tr><td>Gaining speed by stepping one or more times with the inside foot</td><td>Inside foot positioning on the contralateral pedal (and sitting down)</td></tr>
<tr><td>Inside foot through the frame || or || Inside leg swings over the saddle</td><td>Gaining speed by stepping one or more times with the outside foot || and/or || gaining speed by pedalling with the inside foot</td></tr>
<tr><td>Inside foot on contralateral pedal, sitting down</td><td>Outside foot on the ipsilateral pedal (and sitting down)</td></tr>
</table>

<table>
<tr><th>Dismounting category 1</th><th>Dismounting category 2</th><th>Dismounting category 3</th></tr>
<tr><td>Strong braking</td><td>Light braking</td><td>Strong braking</td></tr>
<tr><td>(Off the saddle and) outside foot off the pedal || or || outside foot on the ground</td><td>Off the saddle and inside foot through the frame || or || off the saddle and inside leg swings over the saddle</td><td>(Off the saddle and inside foot on the ground)</td></tr>
<tr><td>Bicycle comes to a halt (under an angle)</td><td>Bicycle (almost) comes to a halt</td><td>Bicycle comes to a halt</td></tr>
<tr><td>(Outside foot on the ground)</td><td>Inside foot on the ground (in front or, or behind, the outside foot)</td><td>Outside foot on the ground || or|| both feet at the same time on the ground || or || both feet one by one on the ground</td></tr>
<tr><td>(Off the saddle and) inside foot through the frame and on the ground || or || off the saddle and inside leg over the frame and on the ground</td><td>Outside foot on the ground</td><td>(Off the saddle and) inside foot through the frame and on the ground</td></tr>
</table>

<table>
<tr><th>Waiting category 1</th><th>Waiting category 2</th></tr>
<tr><td>Strong breaking</td><td>No difference with the normal dismounting and mounting behaviour</td></tr>
<tr><td>(Off the saddle)</td><td></td></tr>
<tr><td>Both feet on the ground (and standing up) || or || one foot on the ground, the other on the pedal (and standing up)</td><td></td></tr>
<tr><td>Bicycle is standing still</td><td></td></tr>
<tr><td>Waiting</td><td></td></tr>
<tr><td>Gaining speed by pedalling with 1 foot (and sitting down) || or || gaining speed by pedalling with one foot and stepping 1 or more times with the other foot (and sitting down)</td><td></td></tr>
<tr><td>Other foot on the pedal</td><td></td></tr>
</table>

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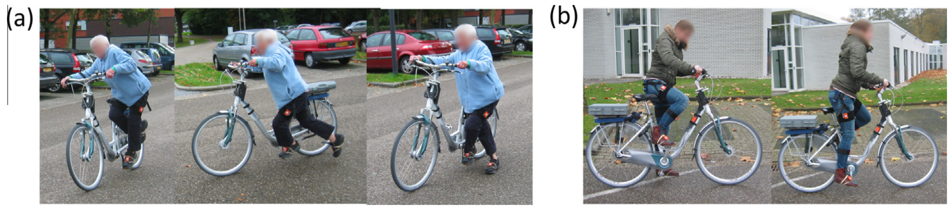

Fig. 4. Mounting of the test bicycle: (a) Starting with positioning of the outside leg on the contralateral pedal, followed by stepping with the inside foot and positioning inside foot on contralateral pedal or (b) Starting with positioning of the inside leg on the ipsilateral pedal, start cycling with inside leg and position outside foot on ipsilateral pedal.

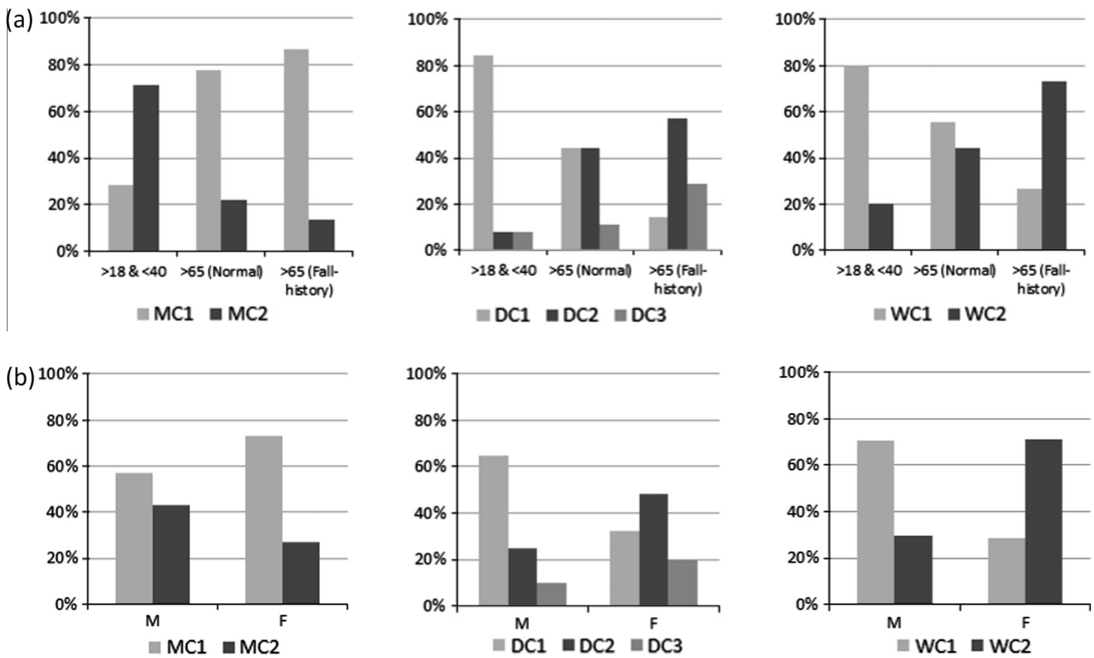

Fig. 5. Distribution of various (dis)mounting and waiting categories by a. age and fall-history group and b. per gender. With MC = mounting category, DC = dismounting category, WC = waiting category, M = male and F = female.

times higher ratio for males of staying on saddle when waiting compared to females ($p = 0.028$, Exp(B) = 5.0).

3.3. Kinematic parameters

A large part of the kinematic data was normally distributed. Analysis of the kinematic data of the (dis)mounting and waiting tasks showed large standard deviations, which could be observed by large spreading in the graphs within both age groups (Fig. 6): Many of the older cyclists (with and without fall-history) demonstrated (dis)mounting kinematics similar to the young participants. For some kinematic parameters the gender and for others the fall-history of the subjects seemed to be of more influence. Several strong correlations between the kinematic parameters were observed, but most relationships were not consistent for all cycling tasks. Strong correlations were observed between bicycle yaw, roll or steer angle and their deviates the angular velocity and angular acceleration, but only the following correlations remained consistent for all cycling tasks: yaw angle and yaw angular velocity (CC 0.5–0.8), roll angle and roll angular velocity (CC 0.6–0.8) and between roll angular velocity and roll angular acceleration (CC 0.5–0.7), steer angular velocity and angular acceleration (CC 0.7–0.8). Furthermore, significant correlations were observed between the different bicycle axis angles (yaw, roll and steer), but only the correlations between bicycle steer angular velocity and yaw angle (CC 0.5–0.6) and yaw angular velocity (CC 0.7–0.8) remained consistent. Similar relationships could be observed for the kinematics of the inside thigh, outside thigh and sternum, with consistent correlations between body part angular velocity and angular acceleration (CC 0.6–0.8). In some cycling tasks, correlations were observed between bicycle and cyclist kinematics (CC 0.4–0.9). Since we only found a limited number of strong consistent relationships, and no consensus exits on which kinematic parameter relates to balance during cycling, all parameters were explored individually as dependent factors.

By means of multi-variate linear regression models we explored the relationships between the kinematic parameters and independent factors gender, age, and all-history. The R^2 is reported to evaluate the model fit. The reference value ($B_{constant}$) belongs to the young male participants and Gender, Age and Fall history were entered as independent factors into the model. For associations with a significant p value of <0.05, the dependent factor reference value (unstandardized coefficient B and confidence interval (CI)), the effects of the corresponding factor (B and CI) are given in Table 3 (for mounting and dismounting during normal cycling) and in Table 4 (during waiting task) and briefly described below.

3.3.1. Normal cycling kinematics

For the *mounting* task the following was observed: The best regression model fit for the dependent kinematic variables was assessed for Inner limb angular acceleration with an $R^2 = 0.33$. Increasing age, a fall history and the female gender were all related

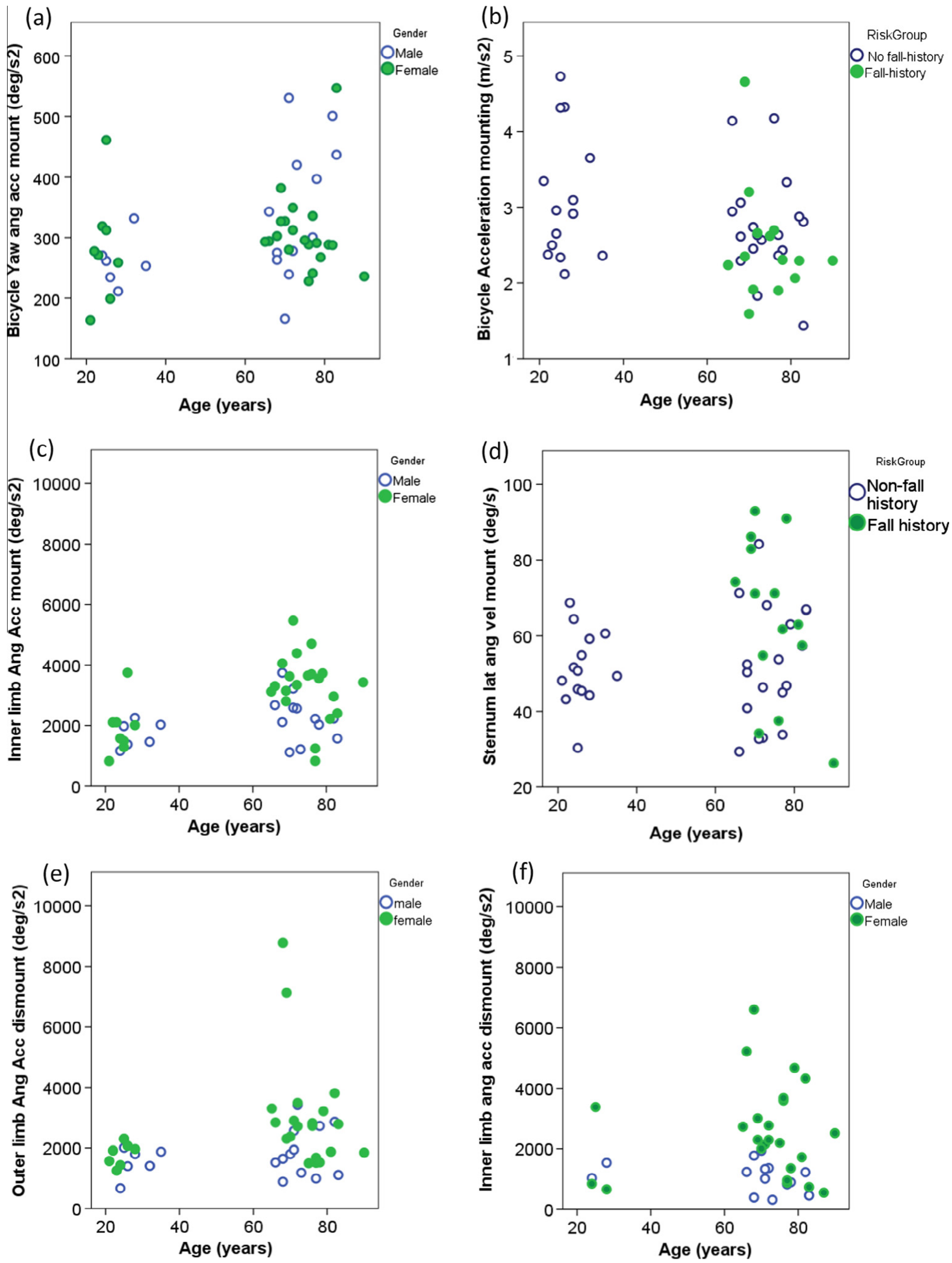

Fig. 6. Effect of age, fall-history and gender on kinematic parameters. Open circles identify no-fall-history or males, filled circles identify fall-history or females (a–d) Mounting task; (e) Dismounting task; (f) Waiting task.

to higher inner limb angular acceleration. with 60%, 10% and 30% respectively (Fig. 6c). Age was related to higher maximum bicycle kinematic values: significantly higher yaw angular acceleration (Fig. 6a) and a trend towards higher maximum steer angle ($p = 0.084$) and steer angular acceleration ($p = 0.053$), but model fit was low ($R^2 < 0.15$). A fall-history was related to 25% higher maximum sternum roll angular velocity and 20% less bicycle acceleration (Fig. 6d and b). Increasing age and a fall-risk did not have a significant effect on mounting velocity, i.e. the cycling velocity at the time the mounting phase ends and harmonic cycling starts. The average older and young cyclist reached comparable cycling velocities of 1.79 ± 0.40 m/s and 1.84 ± 0.41 m/s respectively. Hence at a minimum cycling velocity of 5 km/h (1.39 m/s), all participants had finished mounting.

For *dismounting*, age was only related to total dismount time, with the older participants taking, on average, a full second more to dismount. A fall-history was related to higher bicycle roll angles. Female gender was related to lower bicycle yaw angular velocity. Furthermore, the outer limb angular velocity and acceleration was 40% higher for females compared to males (Fig. 6e).

3.3.2. Waiting kinematics

When *mounting* again after waiting, increasing age and a fall-history resulted in lower mounting velocities at the end of the mounting phase. A fall-history tended to increase maximum steer angles. Increasing age related to significant lower maximum bicycle accelerations. Female gender was related to higher maximum outer thigh angular velocity.

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Table 3
The effects of independent factors age, fall-history and gender on dependent kinematic parameters for Normal cycling with significance level *P* (<0.05), the model fit R^2, and unstandardized coefficient *B* and confidence interval (CI) for reference value (constant) and significant factors from multi-variate linear regression model. Reference value is for Male and Young. ang = angle, vel = velocity, acc = acceleration.

Normal cycling					
Kinematic parameter	R^2	Factor	*B*	95% CI of *B*	*P*
Mounting					
Inner limb ang acc (deg/s^2)	0.33	Constant	1370	764–1978	0.000
		Age	1090	420–1761	0.002
		Fall-history	996	269–1723	0.008
		Gender	779	175–1383	0.013
Sternum roll ang vel (deg/s)	0.21	Constant	57	47–67	0.000
		Fall-history	16	4–29	0.007
		Gender	−10	−20 to 0	0.043
Sternum roll ang acc (deg/s^2)	0.17	Constant	996	770–1221	0.000
		Fall-history	370	100–639	0.008
Steer ang vel (deg/s)	0.15	Constant	83	66–100	0.000
		Gender	−19	−37 to −2	0.029
Steer ang acc (deg/s^2)	0.15	Constant	878	681–1077	0.000
		Age	220	−4 to 444	0.053
Mounting acceleration (m/s^2)	0.14	Constant	2.9	2.4–3.4	0.000
		Fall-history	−0.7	−1.3 to −0.1	0.050
Bicycle yaw acc (deg/s^2)	0.14	Constant	274	222–328	0.000
		Age	72	14–131	0.017
Outer limb ang acc (deg/s^2)	0.12	Constant	1739	1306–2174	0.000
		Gender	428	−4 to 859	0.052
Dismounting					
Outer limb ang vel (deg/s)	0.23	Constant	95	65–126	0.000
		Gender	47	17–77	0.003
Outer limb ang acc (deg/s^2)	0.19	Constant	1172	297–2047	0.010
		Gender	945	75–1815	0.034
Inner limb ang vel (deg/s)	0.13	Constant	159	132–186	0.000
		Fall-history	32	0–64	0.053
Bicycle yaw ang vel (deg/s)	0.12	Constant	19	12–27	0.000
		Gender	−8.5	−16 to −1	0.026
Bicycle roll ang (deg)	0.12	Constant	6.0	4.6–7.5	0.000
		Fall-history	1.9	0.1–3.6	0.034
Time to dismount (sec)	0.09	Constant	3.5	2.5–4.6	0.000
		Age	1.2	0.0–2.3	0.047

The factor gender significantly influenced the kinematics during the *dismounting phase*, showing the difference in dismounting strategy for males and females while waiting. Resulting, the maximum bicycle yaw angle and yaw angular velocity (Fig. 6e), the bicycle roll angular acceleration and steer angular velocities were higher for the females ($p < 0.01$). Also outer limb angular velocities and angular accelerations were at least 50% higher on average for the females ($p < 0.001$) with good model fits of $R^2 = 0.43$ and 0.31 respectively. Similar was observed for the inner limb angular accelerations. Age was related to the time to dismount; the older participants needed on average 4.4 s vs. 2.9 s for the younger participants, respectively. Furthermore, age was related to lower maximum bicycle deceleration, which corresponds to the longer time to dismount with increasing age.

3.3.3. Mounting versus dismounting kinematics

By means of a paired *t*-test, the mounting kinematics were compared to the dismounting kinematics for both cycling tasks normal cycling and waiting combined. The analysis showed that, with exception of the inner and outer thigh angular acceleration and sternum roll angle, all kinematic parameters were significantly different (and higher) for mounting compared to dismounting. For example, sternum roll angular acceleration was 38% higher and bicycle kinematics was up to 80% higher for mounting compared to dismounting (Table 5).

4. Discussion

The aim of this study was to classify the (dis)mounting strategies of young and older cyclists. Several (dis)mounting methods were observed and 2 mounting, 3 dismounting and 2 waiting categories were classified. Both age and gender influenced the choice of (dis)mounting strategy. Secondly, the corresponding bicycle and cyclist 3-dimensional kinematics were assessed and the effects of age, gender and fall-history explored. While overlap was large between the groups, several significant differences were observed and consistent for different cycling tasks: e.g. bicycle yaw angular acceleration increased during mounting as function of age and thigh angular accelerations increased for older participants, females and those with a fall-history. Furthermore, we observed that the bicycle and cyclist kinematics were mainly higher for mounting compared to dismounting.

4.1. (Dis)mounting categories

4.1.1. Young vs. older (dis)mounting category

During mounting, younger subjects lift their inside foot onto the contralateral pedal first and start pedalling. Older subjects however prefer mounting by positioning their outside foot on the ipsilateral pedal and continue with stepping with their inside foot till they reach sufficient speed to be able to position their inside foot on the contralateral pedal ($p = 0.004$, Exp(B) = 16). Several reasons for these differences may be suggested. First of all tradition: older subjects may have learnt to mount a bicycle differently. Secondly, degeneration of balance ability and joint stiffness may require different mounting methods. For example, younger male subjects are used to swing their inside leg over the saddle. Older male cyclists will remain doing so too, as long as their balance ability and joint stiffness doesn't interfere. Changing tactics, by putting the outside foot on the pedal first and then start stepping may help in

Table 4
The effects of independent factors age, fall-history and gender on dependent kinematic parameters for Waiting with significance level *P* (<0.05), the model fit R^2, and unstandardized coefficient *B* and confidence interval (CI) for reference value (constant) and significant factors from multi-variate linear regression model. Reference value is for Male and Young. ang = angle, vel = velocity, acc = acceleration.

Waiting Parameter	R^2	Factor	*B*	95% CI of *B*	*P*
Mounting					
Mounting vel (m/s)	0.22	Constant	2.6	2.0–3.2	0.000
		Age	−0.5	−1.1 to −0.05	0.071
		Fall-history	−0.6	−1.2 to −0.1	0.036
Steer angle	0.21	Constant	21	7–35	0.005
		Fall-history	13	−2 to 29	0.089
Sternum roll ang (deg)	0.19	Constant	29	20–39	0.000
		Age	−10	20–39	0.037
Mounting acc (m/s^2)	0.17	Constant	3.6	2.8–4.3	0.000
		Age	−0.9	−1.7 to −0.2	0.020
		Fall-history	−0.8	−1.6 to 0	0.046
Outer limb ang vel (deg/s)	0.13	Constant	146	100–193	0.000
		Gender	37	3–72	0.035
Inner limb ang (deg)	0.13	Constant	83	66–100	0.000
		Gender	−14	−27 to −1	0.036
Dismounting					
Outer limb ang vel (deg/s)	0.43	Constant	63	24–102	0.002
		Gender	67	38–96	0.000
Bicycle yaw ang (deg)	0.37	Constant	3.8	1.9–5.7	0.000
		Fall-history	−2.3	−4.4 to −0.3	0.024
		Gender	2.7	1.3–4.1	0.001
Outer limb ang acc (deg/s^2)	0.31	Constant	1133	218–2049	0.017
		Gender	1154	478–1830	0.001
Inner limb ang acc (deg/s^2)	0.27	Constant	515	−796 to 1825	0.430
		Gender	1626	657–2593	0.002
Inner limb ang vel (deg/s)	0.23	Constant	77	17–138	0.014
		Fall-history	64	0–128	0.051
Bicycle yaw ang vel (deg/s)	0.24	Constant	8.6	4.3–12.8	0.000
		Gender	5.0	1.8–8.2	0.004
Bicycle roll ang acc (deg/s^2)	0.22	Constant	195	135–255	0.000
		Gender	63	18–108	0.008
Steer ang vel (deg/s)	0.20	Constant	27	10–44	0.003
		Gender	14	2–27	0.028
Inner limb ang (deg)	0.17	Constant	81	60–102	0.000
		Gender	−19	−35 to −4	0.013
Time to dismount (sec)	0.15	Constant	3.0	1.7–4.3	0.000
		Age	1.4	0.08–2.8	0.039
		Fall-history	1.5	0.2–2.9	0.029
Dismounting acc (deg/s^2)	0.13	Constant	3.5	2.7–4.3	0.000
		Age	−0.8	−1.6 to −0.0	0.046
Bicycle roll ang vel (deg/s)	0.13	Constant	13	7–19	0.000
		Gender	4.6	0–9	0.048

Table 5
Results of paired *t*-test comparing mounting and dismounting kinematics, only significant differences are reported with >25% increase in variable. ang = angle/angular, vel = velocity, acc = acceleration, deg = degree, diff = difference.

Paired *t*-test	Mean dismounting	Mean diff mount–dismount	% increase	*P*
Bicycle roll ang (deg)	6.8	2.6	37	0.000
Bicycle yaw ang (deg)	4.7	3.9	82	0.000
Bicycle yaw ang vel (deg/s)	13.5	11.4	85	0.000
Steer ang vel (deg/s)	43.5	35.6	82	0.000
Steer ang acc (deg/s^2)	551.4	354.1	64	0.000
Outer thigh ang (deg)	50.2	22.3	44	0.000
Outer thigh ang vel (deg)	131.2	37.8	29	0.000
Sternum roll ang vel (deg/s)	40.8	13.3	33	0.000
Sternum roll ang acc (deg/s^2)	771.0	294.2	38	0.000

overcoming some of the stiffness and balance problems: the position of the foot on the pedal reduces the relative height of the saddle and a bicycle with some initial velocity becomes more self-stable (Hubbard et al., 2011; Moore et al., 2011; Schwab et al., 2012). The same holds true for female cyclists who need to lift their leg through the frame. For females, hip joint ante-flexion or knee joint flexion stiffness may be limiting factors if the inside foot is to be lifted through the frame first. The time to mount the bicycle and the velocity reached at the end of the mounting task were not significantly different between age groups. While the time to mount tended to be a bit longer for some older cyclists, the cycling velocity at which harmonic cycling started was around 6.5 km/h (SD = 1.4 km/h) for all groups. Apparently, a cycling velocity of at least 5 km/h (= 6.5–1.4 km/h) was required in our study to start comfortable harmonic cycling. Moore et al. (2011) also found that from 5 km/h and faster, the pedalling motion, with corresponding upper body movements, contributes to about 90% of the total motion. Their motion analysis study was performed on a treadmill and the cyclists were asked to cycle from 2 km/h to 30 km/h. Principal Component Analysis showed that at cycling velocities of 2 km/h, the steer and roll and yaw motions contributed to 90% of the total motion and was reduced to about 10% when cycling increased to 5 km/h.

Younger cyclists dismounted their bicycle in the opposite way of mounting it. Most used strong braking and placed their outside foot on the ground first. Most older cyclists however braked lightly and put their inside foot on the ground first when the bicycle was still moving forward, thus requiring additional steps before the bicycle came to a final halt ($p = 0.005$, Exp(B) = 43.5). The older cyclists took about 1 s more time to dismount ($p = 0.05$). The need for speed during mounting and dismounting may reflect the older cyclist's necessity for additional balance of the bicycle–cyclist system to remain upright while performing balance disturbing activities.

4.1.2. Male vs. female (dis)mounting category

Men tend to dismount differently than women, mainly during the Waiting tasks ($p = 0.08$, Exp(B) = 4.2): they tend to stay on the saddle when dismounting or when waiting. The saddle height, together with the difference in body height may explain why: females tend to have more problems reaching the ground with their feet while remaining seated on the bicycle. We didn't observe such influence of gender on mounting category. Therefore, with regards to the higher injury risk after a single-bicycle accident for females, the second hypothesis suggested by Schepers and Klein-Wolt (2012) may have to be adapted to "The way men dismount is safer than the way women generally seem to do". Our study points out the necessity of considering mounting and dismounting as two different entities. So far, mounting and dismounting are grouped into one category in accident analysis (Consumer Safety institute, 2011; Schepers and Klein-Wolt, 2012). However, mounting is not the same as dismounting in terms of chosen strategies and kinematics and therefore, different fall risks and fall risk factors are expected. While males and females use similar mounting strategy, this does not hold true for dismounting. Hence, the strategy used by a cyclist to dismount his bicycle cannot not always be mirrored (reverse sequence) to the strategy used to mount his bicycle.

4.2. Kinematic parameters

The bicycle kinematics corresponded well to reported values of Van den Ouden (2011). From a real life cycling route Van den Ouden assessed average maximum steer angles of 51 deg (vs. 19 deg in our study), yaw velocity 60 deg/s (vs. 21) and yaw acceleration 182 deg/s^2 (vs. 273), and roll angles of 17 deg (vs. 10 deg) and roll acceleration of 108 deg/s^2 (vs. 296). Differences may be explained by the difference in cycling route and variation of and within the age groups. For example, their route included cornering which will have, among others, an effect on the yaw velocity of the bicycle and their adult group included adults up to 55 years of age.

4.2.1. Influence of age, gender and fall-history on kinematics

The assessed differences in (dis)mounting kinematic parameters of the older and young participants could be related to age, gender and fall-history. However, while the difference in average values between the groups was up to 60%, the spreading was large within the groups (Tables 3 and 4, Fig 6). At least half of the older cyclists, with and without fall-history demonstrated (dis)mounting kinematics similar to the young participants. First, a large part of the older cyclists may have been fit enough to compensate for their expected slow decline in physical and mental abilities. Secondly, older (fall-history) cyclists may have compensated for their reduced physical and mental function by adapting their behaviour (Schepers and Klein-Wolt, 2012).

Our findings on the effect of age on bicycle kinematics corresponded well to reported behaviour of elderly compared to younger subjects by Mori and Mizohata (1995) and what each of us can observe daily: older cyclists demonstrate significantly more steering and bicycle yaw accelerations compared to younger cyclists (e.g. for mounting: $p = 0.053$ and $p = 0.017$). In addition, age and gender affected thigh angular velocity and acceleration during (dis)mounting: compared to younger cyclists and males, older cyclists and females had higher inner limb thigh velocities and accelerations while mounting ($p < 0.015$, $R^2 = 0.3$) and females demonstrated higher outer limb thigh velocities and accelerations while dismounting ($p < 0.034$, $R^2 = 0.3$–0.4). This finding, in addition to the generally reduced leg strength for older people and females, may explain the higher injury risk in single bicycle accidents for older cyclists and females compared to younger cyclists and males, respectively.

Fall-history was related to less bicycle acceleration and more sternum and thigh accelerations. This may indicate some leg weakness with compensating upper body behaviour to enhance propulsion. Future accident analysis studies should attempt to study leg strength or another representative value to attain more insight if weak leg muscles may increase fall risk while (dis)mounting a bicycle.

4.2.2. Mounting vs dismounting kinematics

Higher bicycle roll angles, bicycle yaw angles and steer angular velocities and accelerations were observed for bicycle mounting compared to dismounting (Table 5). Also the outer thigh and sternum had higher angular velocities. These findings suggest that mounting a bicycle may be more strenuous and related to higher fall risk than dismounting in a bicycle. However, in real life other factors may play a role, which mainly influence bicycle dismounting, such as fatigue or emergency stops. That other factors are important in injury risk is in agreement with the findings from Kruijer et al. (2013). They reported more single bicycle accidents occurred during dismounting (13%) compared to mounting (9%) among older cyclists ($N = 245$). Furthermore, reported accident factors were: hooking foot during (dis)mounting, sudden braking, balance problems and fatigue. Future accident analysis studies should analyse mounting and dismounting separately and in more detail to attain more insight in accident risks and mechanisms. Especially with the upcoming usage of e-bikes, accident risks may be different due to, among others, the added weight and more complex handling of the bicycle compared to accidents with normal bicycles (Kruijer et al., 2013; Schepers et al., 2014b).

4.3. Study limitations

This study did not look into the effects of physical or cognitive abilities of the participants on (dis)mounting strategy and performance. Cognitive and physical abilities may influence balance during cycling, as it does during gait and stance (Van Schoor et al., 2002). In future, cycling motion analysis or accident analysis studies should include (retrospective) analysis of these relationships to increase insight in the underlying fall risk mechanisms of older cyclists.

We aimed to include older cyclists with a fall-history in this study to be able to explore potential fall risk. Fall-history could, to some extent, be successfully related to kinematic parameters like inner thigh accelerations, but could not be related to (dis)mounting strategy. However, during the cycling experiments and video analysis we observed that many older cyclists in the non-fall-history group cycled as risky as the fall-history group, for example: they had difficulties lifting their leg over the frame, almost lost balance as frequently and or demonstrated criss-cross cycling over the road during mounting phase. On questioning, several of the non-fall-history group participants mentioned that they had adapted their cycling behaviour in terms of buying a bicycle with extra low step-in, changing the time of day to go cycling to avoid heavy traffic, etcetera. On the contrary, several older cyclists in the fall-history group cycled very well and just had bad luck in being involved in a single-bicycle accident: e.g. due to sudden breaking or sudden extreme manoeuvring to avoid a dog or another road user. Therefore, older cyclists with a history of multiple falls within a short period of time might be more representative of a fall-history group and demonstrate clearer differences in strategies and kinematics with respect to non-fallers during cycling tasks. However, most cyclist with multiple falls may have stopped cycling or might be exposed to high fall-risk during a scientific study.

The wireless inertial movement sensors enabled us to record (dis)mounting of the bicycle without cables being in the way or forming potential fall risk for the participants. Therefore, we observed relatively natural mounting and dismounting behaviour and could assess corresponding 3-dimensional cycling kinematics. However, we had some loss of data occurring during the cycling measurements, among others, due to the wireless communication between inertial movement sensor and receiver. On colder days or during prolonged testing, battery time was an issue. Although 3-dimensional inertial movement sensors seem to have become common practice in laboratory motion analysis (Roetenberg, 2006; Marin-Perianu et al., 2011), the state of the art wireless technology still has practical measurement issues. When working outside, with elderly participants or patients in general, it is tedious and sometimes impossible to repeat measurements. Loosing data during such extensive testing should be avoided. Therefore, the robustness of the wireless sensor system needs to be further improved.

4.4. Recommendations

In the video analyses we observed many different body part actions with varying chronologic order. By focussing on defining the inner or outer leg that starts the (dis)mounting motion, we were able to narrow down the many possibilities to (dis)mount a bicycle into 2–3 categories. This simplification enables a good comparison between (age, gender, risk) groups. However, the individual steps may play a role in fall risk or bicycle design issues and should be taken into account in future studies on (dis)mounting.

Insight into the underlying mechanisms of (dis)mounting falls may be improved by analysing mounting and dismounting as separate entities in accident or experimental studies. More details should be gathered during accident analysis studies: not only regarding the accident type, but also about the situation, timing and personal characteristics.

Our study has shown that, compared to young and male cyclists, older cyclists and females may be at higher risk of sustaining a fall during (dis)mounting due to higher thigh and bicycle yaw accelerations, which may be related to the way they (dis)mount their bicycle. Being able to sit on the saddle with the feet on the ground, as most men are able to do, seems to be related to lower thigh accelerations and hence less strength required to support the body weight. Therefore, a bicycle on which the cyclist is able to sit on the saddle with feet on the ground would be beneficial for the older and female cyclists. A low step-in may refrain the older cyclists from the need of putting the outside foot on pedal first and stepping to be able to get inner limb through the frame. Furthermore, an electrical support may enable older cyclists to accelerate faster to a more stable mounting velocity, thus enhancing their balance. In conclusion, several easy design adjustments can be made to a regular bicycle to support older and or female cyclists during (dis)mounting.

5. Conclusions

This study is the first to categorize and analyse the different ways older and younger subjects (dis)mount their bicycles. These classifications may be used in future accident analyses to attain more insight in fall risk during (dis)mounting a bicycle.

The cyclists in our study required a cycling velocity of at least 5 km/h to finish their bicycle mounting phase and start harmonic cycling.

Dismounting is not the same as reversed mounting. Furthermore, higher bicycle yaw and roll angles and higher thigh and sternum angular velocities were observed during mounting compared to dismounting. Therefore, different injury risks and risk factors may be related to the mounting and dismounting. In future, these cycling tasks should be analysed separately.

Thigh angular velocity and accelerations were related to age and gender during (dis)mounting. At present it is not clear if these differences are caused by the chosen mounting strategy or by differences in physical and or cognitive abilities.

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