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In-Depth Evaluation of Association between Crash and Hand Arthritis via Naturalistic Driving Study

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Abstract: Severe arthritis can limit a driver's range of motion and increase their crash risk. The high prevalence of arthritis among the US driver population, especially among senior drivers, makes it a public safety concern. In this study, we evaluate the impact of arthritis on driving behavior and crash risk using the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS), which collected continuous driving data through data acquisition systems installed on participant's vehicles. A detailed questionnaire survey was administered on demographic, health conditions, and personality information at the time of recruitment. The dataset includes 3563 participants. Among them, 78 drivers were identified to have severe arthritis, and they contributed to 414 out of 1641 crashes. We systematically evaluated the impact of severe arthritis on crash risk, secondary task engagement, and fitness-to-drive metrics. The results show there is a significant relationship between arthritis and crash risk, with an odds ratio of 1.99 with adjustment for age effects, which indicates that individuals with arthritis are twice as likely to be involved in a crash. There is no statistically significant association between arthritis and secondary task engagement, as well as the sensation-seeking scores, a personality trait.

Keywords: arthritis; crash risk; secondary task engagement; driver fitness-to-drive; naturalistic driving study

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1. Introduction

Rheumatoid arthritis is a health condition that is characterized by the inflammation of joints that can limit an individual's range of motion. In the United States, approximately 54 million individuals are diagnosed with arthritis, and among them, 24 million had activity limitations attributable to the condition [1]. Arthritis typically develops with age, and approximately 50% of individuals over the age of 65 have been diagnosed with arthritis [1]. Severe arthritis may increase the driver's crash risk due to a reduced range of joint motion and pain. The high prevalence of arthritis among the driver population is a safety and public health concern, especially among senior drivers. There is a need to understand the impacts of arthritis on crash risk and driving behavior because this understanding will provide critical information for the development of assistance systems that improve the safety and mobility of drivers with arthritis.

Scholars have shown that individuals with rheumatoid arthritis could have deteriorated driving performance and difficulty in driving [2,3]. Jones et al. [4] indicated that drivers with rheumatoid arthritis and osteoarthritis had difficulty conducting common driving tasks, including buckling the seat belt, looking over one's shoulder to check blind spots, turning the wheel, and using the hand brake. Similarly, Vrkljan et al. [5] showed that drivers with arthritis experienced problems that could affect safety. However, the authors of these studies also suggest that the majority of the difficulties with the driving task would not necessarily affect safety. Proper techniques, such as threading steering and backing up using mirrors can effectively mitigate the impairment associated with arthritis [4].

Relatively few studies have directly linked arthritis with crash risk, and inconsistent results have been reported. McGwin et al. [6] conducted a population-based case-control study of chronic medical conditions and crashes among older drivers. The study found that arthritis was associated with an increased risk among females (odds ratio [OR] = 1.8) but not among males (OR = 0.8). A 5-year cohort study (1991–1995) by Sims et al. [7] based on police-reported crashes in Alabama for 174 senior drivers (>55 years old) revealed that there is no association between arthritis and crashes. Similarly, in a cohort study of 1791 older drivers, Foley et al. [8] found no association between arthritis and crash involvement. The inconsistency in the relevant literature suggests that in-depth studies are needed to fully understand the safety impacts of arthritis.

Fitness-to-drive has been a major safety and mobility concern for senior drivers, and it can be directly affected by arthritis [9]. Researchers have shown that the fitness abilities of senior drivers can affect both driving safety and the decision to give up driving. Guo et al. [10] showed that fitness-to-drive is a key reason that seniors give up driving. Using naturalistic driving study (NDS) data, Antin et al. [11] showed that certain fitness measures, including upper body strength, are associated with increased crash risk. Because drivers with arthritis or other fitness conditions tend to drive less than others, arthritis could be a factor underlying the well-documented low-mileage-bias (LMB) issue for senior drivers. The LMB refers to the phenomenon that senior drivers with lower annualized mileage are at significantly higher risk compared to drivers with higher annualized mileage [12]. The connection between arthritis and these known risk factors can help shed light on the causal path for arthritis and crashes.

Arthritis can also affect driver behavior, such as cellphone use and other secondary tasks. Secondary task engagement, which has been defined as "attention given to non-driving-related activity, typically to the detriment of driving performance" [13], has been shown to be a critical reason for crashes, causing about 1.2 million crashes and contributing to 16% of all fatal crashes in 2008 [14]. Secondary tasks such as cellphone use have a high prevalence among drivers and can significantly increase driving risk [15,16]. Guo et al. [17] examined secondary task engagement by age group and showed that, compared to middle-aged drivers (35–65 years old), senior drivers (≥65 years old) were much less likely than others to be engaged in secondary tasks (40.49% vs. 51.68%) and cellphone use (0.87% vs. 5.30%). However, the relative risk associated with distraction was much higher, with OR = 1.71 versus 1.58 for overall distraction and OR = 5.72 versus 2.11 for cellphone use. Examining whether arthritis plays a role in the prevalence and relative risk of distraction can improve the general understanding of the risk for senior drivers.

The majority of existing arthritis-related studies have relied on self-reported online surveys, or interviews or experiments with relatively small sample sizes. Large-scale NDSs enable researchers and policymakers to observe driver behavior and crash risk under real-life driving conditions [18,19]. The participants of an NDS will drive an instrumented vehicle with no specific instructions under real-life driving conditions for an extended period of time. The instrumented vehicles, typically the participants' own, are equipped with a nonintrusive data acquisition system (DAS). The DAS is capable of recording comprehensive driving data, including GPS, radar, acceleration, and multi-channel video, capturing both the environment and the vehicle interior. Large NDSs are typically accompanied by surveys to gather demographic information, health conditions, crash history, and other information. The combination of comprehensive driving data and survey data provides an opportunity to draw insight into crash causation, driver risk factors, and potential safety countermeasures.

The inconsistency in the relationship between arthritic and crash risk, as well as the association between arthritis and other known risk factors, deserves in-depth research using novel data sources. In this study, we attempt to fill in the knowledge gap by utilizing the SHRP 2 NDS dataset to assess the impact of arthritic and crash risk, as well as the association of arthritis with other risk factors. The HPR 2 NDS is the largest NDS to date, with more than 3400 participants and 1 million hours of continuous driving data. The objectively collected naturalistic dataset provides accurate information about the moment the crashes happened and the driver's behavior under normal driving conditions. The NDS data provide complementary evidence to studies based on self-reported crashes (Anstey et al. [9] and Hong et al. [20]). A comprehensive analysis was conducted to examine the association between arthritis and crash risk, secondary task engagement, driver personality, and fitness-drive information.

2. Methodology

Linear and logistic regression models were used in the analysis, depending on the type of response variable being analyzed. For both types of models, a driver-specific random effect was included to account for the correlation among observations from the same participant [19]. Model details are provided in the following two subsections.

2.1. Random-Effect Logistic Regression Model

A logistic regression model was adopted for predicting binary response variables. Two types of binary response variables were evaluated: whether an event is a crash or not, and whether the driver was engaged in a secondary task or not,

$$Y_{ij} = \begin{cases} 1 \text{ crash (or secondary task usage)} \\ 0 \text{ no crash (or no secondary task usage)} \end{cases}, \ i = 1, \ldots, I, \ j = 1, \ldots, J_i$$
$$or$$
$$Y_{ij} = \begin{cases} 1 \text{ the driver was engaged in secondary task)} \\ 0 \text{ The driver was not engated in secondary task)} \end{cases}, \ i = 1, \ldots, I, \ j = 1, \ldots, J_i$$

for ith driver, $i = 1, \ldots, I$ and jth event for driver i, $j = 1, \ldots, J_i$.

The logistic regression model can be formulated as follows. Assuming that the response variable Y_{ij} follows a Bernoulli distribution:

$$Y_{ij} \sim Bernoulli\ (p_{ij})$$

where I is the number of drivers and J_i is the number of observations for driver i; p_{ij} is the probability of $Y_{ij} = 1$. A logit link function was used to link the probability of having a crash (p_{ij}) with a set of covariates, as shown below.

$$logit(p_{ij}) = log\left(\frac{p_{ij}}{1 - p_{ij}}\right) = \beta_0 + \beta_1 X_{1ij} + \beta_2 X_{2ij} + \ldots + \beta_k X_{kij} + z_{ij} u_i,$$

where X_{ki} is the variable for potential factor k, and β_k is the corresponding regression coefficient. $\beta_k = 0$ indicates there is no significant association between the response variable and factor X_k. For the binary factors, $\exp(\beta_k)$ is the OR associated with the factor. Several factors were included in the model, including arthritis status, age, and sex. The u_i is a vector of mixed effects and z_{ij} is the corresponding design matrix. The term $z_{ij} u_i$ ensures that all observations from driver i share the same random term u_i, adding the unique characteristics of a driver to the model. Commonly, μ_i is assumed to follow a normal distribution with a mean that is equal to zero and the variance being estimated from the data.

2.2. Random-Effect Linear Model

A random-effect linear model was adopted for predicting continuous response variables, including the driver's right-hand grip strength and the sensation-seeking score (SSS). Similar to the random-effect logistic model, a random-effect term is used to include a driver-specific correlation. The random-effect linear model can be formulated as follows:

$$Y_{ij} = \beta_0 + \beta_1 X_{1ij} + \beta_2 X_{2ij} + \ldots + \beta_k X_{kij} + z_{ij} u_i \ \ i = 1, \ldots, I, \ j = 1, \ldots, J_i$$

where I is the number of drivers, J_i is the number of observations for driver i, u_i is a vector of mixed effects, and z_{ij} is the corresponding design matrix. The $X'_{kij}s$ are the arthritis condition and demographic characteristics such as age and sex.

3. Dataset

This study used the SHRP 2 NDS dataset. The dataset includes 3563 participants from six US sites in Florida, Indiana, North Carolina, New York, Pennsylvania, and Washington. The participants' vehicles were instrumented with an advanced DAS that collected dozens of key driving variables, including four-channel video views, GPS, three dimensions of acceleration, and the yaw rate. The driving data were continuously collected from ignition-on to ignition-off at various frequencies (e.g., videos at 10 Hz and GPS at 1 Hz). Each driver participated for 1 or 2 years, and the data were collected between 2010 and 2015 [10].

In this study, we used two datasets: driver information survey results and driving events. The driver information survey was conducted at the time of recruitment, including age group, sex, personality traits such as the SSS, physical fitness, and medical conditions, including arthritis status. The SSS is a questionnaire-based assessment metric on a scale from 0 to 40, measuring the willingness of an individual to participate in new or intense situations. Individuals with high scores are likely to be sensation seekers. The participants also went through a series of physical exams that included metrics such as hand grip strength. A list of variables is presented in Table 1.

Table 1. Summary Statistics for the Analyzed Variables.

Variable Name	Description	Summary Statistics
Age	~	Young: 2016 drivers, middle-age: 634 drivers, and senior: 888 drivers
Sex	~	47% male; 53% female
SSS	Estimate of how willing an individual is to participate in new or intense situations (range: 0–40).	Mean = 14.58; Std = 6.88; Q1 = 9; Q3 = 20
rtHnd1st	Reading from the JAMAR hand dynamometer for the participant's right hand (kg)	Drivers with arthritis: Mean = 63 kg; Std = 24.2 kg Drivers without arthritis: Mean = 51 kg; Std = 22.84 kg
Secondary Task Frequency	How frequently the driver was involved in a secondary task during driving	Yes = 54% (12% interacting with a passenger in the adjacent seat, 7% talking, 7% cell phone use, 7% other external interaction, 2% monitoring radio, and others)

The second dataset (i.e., the event dataset) provides unique insights into both the natural driving behaviors of drivers and the driving environments. The event dataset includes two types of events, crashes and control driving segments, or baseline epochs. The control driving segments are short (6 s) driving segments under normal, non-safety-critical conditions. The controls were randomly selected following a case-cohort approach, and can be used to evaluate the prevalence and risk associated with other variables [18,19]. Trained data reductionists reviewed the videos of a crash (5 s before the precipitating event of the crash until the end of the event) and annotated dozens of parameters related to driver behavior, traffic conditions, and driving environment following the protocol described in *SHRP 2 Researcher Dictionary for Video Reduction Data*, Version 3.4 (https://insight.shrp2nds.us (accessed on 10 October 2022)). The same data reduction protocol was used to extract information for around 20,000 randomly selected control driving segments.

4. Results

4.1. Summary Statistics

Among the 3563 drivers who participated in the NDS, 78 drivers (34 males and 44 females) had severe arthritis and contributed to 414 of the 1641 crashes. The driver age ranged from 18 to 94 years old. As shown in Figure 1, the percentage of participants with arthritis increases with age. There is a major jump from the 50–54 years old age group (1.7%) to the 55–59 years old age group (6.0%). Another jump in percentage is shown for drivers above 80 years old. The prevalence of arthritis is compatible with the US population, as shown in Table 2 [1]. The driver distribution of crashes by age group is given in Figure 2. In Table 3, crash types and severity for drivers with arthritis is given.

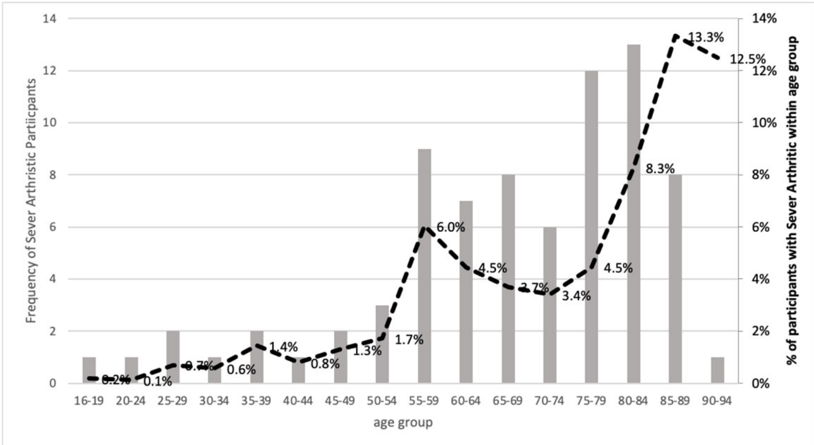

Figure 1. SHRP 2 driver distribution of arthritis by age group.

Table 2. National and SHRP 2 Prevalence of Arthritis [1].

Group Age	w_i
Teenage (16–19)	0.051
Young adult (20–29)	0.176
Middle-aged (30–64)	0.630
Senior (+65)	0.143

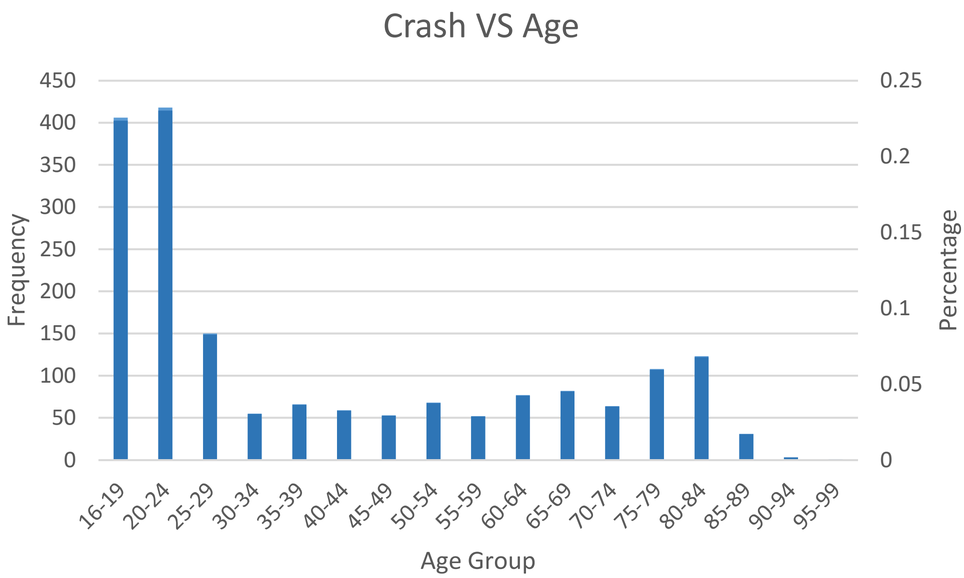

Figure 2. SHRP 2 driver distribution of crashes by age group.

Table 3. Crash Types and Severity for Drivers with Arthritis.

Crash Type	Total
Animal-related	3.54%
Backing into traffic	1.14%
Backing, fixed object	4.52%
Opposite direction (head-on or sideswipe)	0.16%
Other	5.72%
Pedal cyclist-related	0.16%
Pedestrian-related	0.16%
Rear-end, striking	6.48%
Rear-end, struck	6.32%
Road departure (end)	7.14%
Road departure (left or right)	59.75%
Sideswipe, same direction (left or right)	0.98%
Straight crossing path	0.93%
Turn across path	1.42%
Turn into path (opposite direction)	1.03%
Turn into path (same direction)	0.54%
Total crashes	414

4.2. Association between Arthritis and Crashes

The relationship between arthritis and crashes was evaluated using the SHRP2 event dataset, which is based on the case-cohort epidemiological study design [19]. The crashes and control driving segments by arthritis status are shown in Table 4. As can be seen, the prevalence of arthritis among crashes (3.8%) is higher than among control driving segments (2.2%).

Table 4. Arthritis and Crash Frequency.

	Arthritis	No Arthritis	Total
Crashes	62 (3.8%)	1565 (96.2%)	1627 (100%)
Control Driving Segments	400 (2.2%)	17,394 (97.8%)	17,794 (100%)
Total	462	18,359	19,421

The formal inference was conducted with a mixed-effect logistics regression model. Age groups and gender are included in the model to adjust for potential confounding and interaction effects. The random-effect model was implemented in R using the "lme4" package. The outputs of the model are presented in Table 5. Both age and arthritis are significantly associated with crash risk. The age variable included three groups: young (18–35), middle-aged (35–64), and senior (65+). After adjusting for the age and sex factors, severe arthritis is significantly associated with an increased crash risk with an OR of $\exp(0.69) = 1.99$. That is, drivers with arthritis were twice as likely to be involved in a crash than drivers without arthritis.

Table 5. Random-effect Model for Crash Risk.

	Coefficient Estimates	Odds Ratio	*p*-Value
Intercept	2.68	-	<0.001
Arthritis	0.69	1.99	<0.001
Middle-aged vs. Young	0.41	1.51	<0.001
Senior vs. Young	0.17	1.19	0.048
Male vs. Female	0.06	1.06	0.422

Arthritis was shown to not have any interaction with age. The variable representing the interaction between arthritis and the senior age group had a p-value of 0.44. The variable representing the interaction between arthritis and the middle-aged group had a *p*-value of 0.83. This indicates that there is no interaction between arthritis and the age of the driver variables, and thus, a random-effect model is sufficient for distinguishing the effects of arthritis on crash risk from the driver age.

4.3. Association between Arthritic, Secondary Task Engagement, SSS, and Right-Hand Grip Strength

Due to the pain and stiffness associated with arthritis, drivers with arthritis may be less likely than others to engage in secondary tasks. We used the control driving segments to examine this potential association. Crashes were not used, as the goal was to examine secondary engagement during normal, non-crash driving conditions. The frequency of secondary task engagement according to arthritis status is shown in Table 6. Among observations from drivers with arthritis, the prevalence of secondary task engagement is significantly lower (42.8% vs. 52.1%, chi-square statistic = 3.8, *p*-value = 0.000203). However, when accounting for age as a confounding factor with the random-effect model, arthritis was not a significant contributor to secondary task engagement (Table 7). Therefore, the association between secondary task engagement and arthritis is confounded with age.

Table 6. Arthritis and Secondary Task Frequency.

	Secondary Task	No Secondary Task	Total
Arthritis	171 (42.8%)	229 (57.3%)	400 (100%)
No Arthritis	9066 (52.1%)	8323 (47.9%)	17,389 (100%)
Total	9237	8552	17,789

Table 7. Random-effects Model Outputs on Secondary Task Engagement.

	Estimate	OR	*p*-Value
Intercept	0.31	-	0.000
Arthritis	0.14	1.15	0.300
Middle-aged vs. young	0.37	1.45	<0.001
Senior vs. young	0.72	2.05	<0.001
Male vs. Female	0.02	1.02	0.504

The SSS is an estimate of how willing an individual is to participate in new or intense situations. Individuals with high scores, on a scale from 0 to 40, are more likely than others to be sensation seekers [21]. Researchers have shown that drivers with a high SSS are likely to be risky drivers and to have a greater crash risk than others [22]. A regular linear model with age and sex indicated that arthritis was not significantly associated with a driver's SSS (Table 8).

Table 8. Linear Model to Predict the SSS of a Driver.

	Estimate	*p*-Value
Intercept	15.93	0.000
Arthritis	0.59	0.387
Middle-aged vs. Young	4.65	<0.001
Senior vs. Young	6.94	<0.001
Male vs. Female	2.48	<0.001

Scholars have shown that hand function deteriorates among people with arthritis [23]. We used the strength of the driver using right-hand grip strength as an indicator of body strength. The goal is to test the association between the arthritis right-hand grip strength of the driver. Unexpectedly, the results show that the drivers with arthritis were stronger than those without, with adjustment for age and sex (Table 9). This is different from what previous studies have found, and thus, we recommend more research efforts to be conducted to verify and to justify the crash risk of drivers with arthritis [24].

Table 9. Linear Model to Predict the Right-hand Grip Strength of a Driver.

	Estimate	*p*-Value
Intercept	56.02	0.000
Arthritis	5.58	0.002
Middle-aged vs. Young	3.08	<0.001
Senior vs. Young	16.72	<0.001
Male vs. Female	33.02	<0.001

5. Limitations of the Study

Although SHRP2 NDS has the largest number of participants, the recruitment was based on voluntary samples, which may bring bias to the assessment. Due to the limitation of the dataset, the effects of external factors such as road conditions, traffic density, and weather conditions were not accounted for in this study. However, more than 90% of the crashes in the dataset occurred in either clear or cloudy weather, and thus, the weather effect might be limited in this dataset [18,19]. Additionally, the weather and traffic density was found to be correlated with secondary task engagement by a previous study [24]. In this study, we found that arthritis is not a significant contributor to secondary task engagement.

6. Summary and Discussion

Arthritis can negatively affect driving safety and mobility, which especially impacts the senior driver population with a high prevalence of arthritis. Determining the impact of arthritis on crash risk and driver behavior could provide critical information to assess the fitness-to-drive of senior drivers, and aid in the development of driving assistance systems. Using the largest naturalistic study to date, the SHRP 2 NDS, this paper provides insights into the relationship between arthritis and crash risk, and secondary task engagement, personality traits, and physical fitness-to-drive factors.

The results show that arthritis is significantly associated with crash risk. Specifically, the crash risk for the drivers with arthritis was twice that for the arthritis-free drivers. This significant effect has been adjusted for age and sex factors through the mixed-effect logistic regression model. The finding indicates that arthritis does increase driving risk, even after the consideration of age, a known confounding factor. There is a need to explore the causal path for increased risk (i.e., the aspects of driving capability that arthritis impairs that lead to increased risk).

In this study, we took the first step to reveal the aforementioned causal path by assessing the impact of arthritis on secondary task engagement, sensation-seeking, and right-hand grip strength. The results indicate that there is no significant association between arthritis and secondary task engagement after controlling for age. Therefore, the increased crash risk among drivers with arthritis is not likely to be linked to secondary task engagement. Similarly, there is no evidence that arthritis is associated with SSS. Unlike previous studies, right-hand grip strength was not found to be weak for drivers with arthritis, and thus, there is no evidence that grip strength is a cause for the increased crash risk.

Using the novel, objectively collected NDS data, this study provided evidence in support of the significant association between arthritis and crash risk. We hypothesize that the root reason for the elevated risk could be the limited range of joint motion or pain, which impairs the safe operation of the vehicle or leads to a slower response to safety-critical situations. Additional in-depth studies with properly measured information must be conducted to identify the causal pathway for the increased crash risk, and ultimately to develop driving assistant systems to improve the safety of drivers with arthritis.

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Data Availability Statement: This study used the SHRP 2 NDS dataset, which is owned by Virginia Tech Transportation Institute. It cannot be shared publicly, but as a request.

Conflicts of Interest: The authors declare no conflict of interest.

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