A STUDY OF CYCLISTS HAND-ARM VIBRATION EXPOSURE

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Abstract

Cycling infrastructure and, in particular, a well maintained pavement surface contributes to a safe and comfortable ride. However, defective pavement surfaces and insufficient maintenance can expose cyclists to excessive hand-arm vibration. Limited data is available regarding cyclists' exposure to hand-arm vibration. Advances in low-cost electronics engineering has provided a range of vibration sensors and recording media. Instrumented probe bicycles can be constructed with low-cost apparatus to allow a broad range of data to be collected. Details of the design and construction of a low-cost hand-arm vibration measurement system are provided. Measurements comply with EN ISO 5339-1:2001 with a sample rate of 5 kHz and the application of frequency weighting filters (W_h). Partial exposure data ($A(8)_t$ ms^{-2} r.m.s.) are provided for a range of cycling infrastructure surfaces in Edinburgh. Preliminary findings of a medical screening survey (n = 555) are also presented. The results show that there is a potential public health issue associated with cycle delivery couriers, commuters and recreational cyclists riding on unsuitable and poorly maintained pavement surfaces for prolonged periods of time.

1. Introduction

The management of pavement surfaces for walking and cycling is currently a labour intensive task and relies upon user reporting defects and direct visual inspection. Local authorities are being pressed to cut budgets and reduce annual expenditure. Therefore, pavement surfaces associated with walking and cycling are seldom considered to be an investment priority. A defective pavement surface discourages cycling activity and vibration exposure has been identified as a consequence of poor cycle track quality (Bíl et al., 2015). Through an online survey of experienced cyclists (>2000 km per year), Ayachi et al. (2015) conducted principal component analysis of the results and identified that road surface condition, bicycle saddle and frame design contribute significantly to rider comfort. Gao et al. (2018) conducted a surveys of pavement surface quality using a combination of user perception questionnaire surveys and an instrumented bicycle.

Previous research has assessed the relative contribution of bicycle components on the vibration induced in the hands and buttocks of cyclists. Lépine et al. (2015) assessed the relative contribution of vibration through measurement in three different locations. These included the vertical force and acceleration transmitted via the saddle, force and acceleration transmitted through the handle bars and,

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finally, the force and acceleration transmitted to the hands on break hoods and the handle bars under the hands. Gomes and Savionek (2014) conducted hand-arm vibration exposure on three pavement surface types: asphalt, precast concrete and interlocking concrete blocks. Using a tri-axial piezoelectric accelerometer fixed to the handle bars, daily exposure to vibration (A(8)) for a daily duration of exposure of two hours (T=2 hrs) was considered to represent an average exposure time for leisure cycling purposes. Parkin and Eugenie Sainte (2014) provided a study of comfort and health factors including the nature of vibrations from riding in different circumstances in the city of London. Munera et al. (2014) summarised the different standards and guidelines associated with the evaluation of vibration and exposure limits whilst cycling. They focused upon physiological and pathological disorders in performance athletes. The research identified the application of the Directive 2002/44/EC11 in defining the limit of exposure and the limit triggering action for cyclists' vibration exposure. Furthermore, they identified ISO 5349-1 a suitable method for examining cyclists' vibration exposure. Munera et al. (2018) analysed the dynamic and physiological response of the human body under different vibration frequencies whilst cycling.

Hölzel et al. (2012) measured cyclists' exposure to vibration induced by four different cycle path pavement surfaces: asphalt, concrete paving slabs, cobblestones and self-binding gravel. They concluded that cycling pavement surfaces constructed from asphalt improve rider comfort and may encourage greater uptake of cycling. In a review of instrumented probe bicycle (IPB) research, Mohanty et al. (2014) summarised the development of comfort and safety prediction models highlighted the need to collect more accurate and continuous real-time data that represents the cycling experience.

The research aims to contribute improved data collection procedures for the maintenance of cycling infrastructure provision. The present study examines the public health implications of defective pavement infrastructure to professional, commuter and recreational cyclists. A self-reported vibration exposure symptom survey was also conducted (n=555). The questionnaire explored cyclists' experience of vibration exposure symptoms with specific questions providing medical screening of comorbid disease and medical procedures. The preliminary findings of field measurements and the self-reported symptom questionnaire survey are presented. The results provide an insight into the potential prevalence of hand-arm vibration exposure symptoms among recreational and commuter cyclists in Edinburgh.

2. Data collection methods

Two research methods were adopted: (i) the instrumented bicycle and (ii) an online survey of self-reported vibration exposure symptoms. The following sections provide specific details of the methods adopted for the study.

2.1. Instrumented bicycle

An aluminium framed Trek 6000 (m = 13.9 kg) was selected as the bicycle platform for the instrumented probe. The bicycle was selected as a typical commuting, sports and recreational bicycle type witnessed in the Edinburgh. There are many variables associated with the power supplied by a cyclist to provide the locomotive force. These include the mechanical efficiency of the bicycle, the mass of the rider, the mass of the bicycle, the coefficient of rolling resistance, the gradient of the surface, aerodynamic drag, frontal area of the rider and the headwind velocity. Furthermore, parameters associated with the tyre tread pattern, tyre pressure and the movement of shock absorbers can significantly vary the repeatability of the data collected. Figure 1 shows the bicycle and equipment configuration.

Figure 1 Instrumented probe bicycle equipment configuration.

It is essential that human vibration exposure is quantified by the vibration conditions at the interface between the environment and the human body: not by the vibration at any other arbitrary position on the body or in the vibration environment (Griffin, 1990). Therefore, a grip adaptor was constructed from a stereolithography file using a 3D printer and was printed from acrylonitrile butadiene styrene (ABS) thermoplastic polymer. Figure 2 shows the grip adaptor and the mounting position on the handlebar.

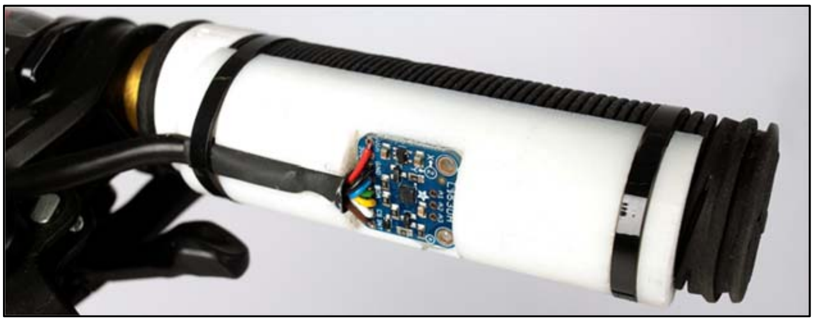

Figure 2 Handle bar grip adaptor mount position.

Two three axis micro-electro mechanical accelerometers (LIS3DH) were mounted on the handle bars using the constructed grip adaptor. The accelerometers sample rate was 5 kHz. A micro controller (Teensy 3.2) and compact computer (Raspberry Pi 3) were used to control data capture and storage. A bespoke GPS device including a (MTK3339), micro controller and micro SD card was mounted on the rear luggage rack to assist with gathering location information for future analysis.

All digital signal processing was undertaken using Matlab 2017a. Toolbox add-ons included the Control System Toolbox (Version 10.2), Digital Signal Toolbox (Version 9.4) and Signal Processing Toolbox (Version 7.4). Digital filters (W_h) were constructed in accordance with ISO 5349 (BSI, 2001) using continuous time transfer functions.

2.2. Self-reporting vibration symptom questionnaire survey

The target population was Edinburgh based commuter and recreational cyclists. The survey was piloted in March 2018 on a pilot sample of members of the target population. This process allowed identification of respondents having issues understanding the questions or the specific logical sequence of questions. Pilot respondents provided feedback in relation to these matters and the survey instrument was amended.

Non-random convenience sampling was considered for the survey. The sample was constructed of individuals who were easiest to recruit, e.g. University colleagues, students, medical staff and those active on social media. Social media was used to advertise the survey with support from Spokes and other Scottish cycling interest groups. Snowballing of survey responses was also undertaken; as one respondent completed the survey they were encouraged to recommend other suitable respondents to be surveyed.

The research considered commuter and recreational cyclists exposure to hand-arm vibration and their potential development of symptoms associated with excessive hand-arm vibration exposure. The questionnaire was divided into three sections: (i) cycling activity, (ii) self-reported HAV symptoms and (iii) medical screening.

The first section collected data concerning general cycling activity and examined continuous and categorical data associated with exposure to cycling and riding position. Suspension was also considered as this has significant implications for vibration exposure whilst cycling. The questions specifically requested information relating to the number of years the respondent has been cycling; number of days in a week spend cycling; hours cycling per day; bicycle riding position; type of bicycle ridden most often; and does the bicycle most often used have suspension.

The second section questioned respondents on their experience of hand-arm vibration exposure symptoms. These were categorised as: blanching; cold sensation; stiffness; swelling; pain; tingling; numbness (lack of sensation); and weakness. Respondents were questioned regarding the longevity of their symptoms and if the symptoms experienced were associated with work related activities or cycling. The third section examined medical conditions associated with neuropathies of the hands and vibrating tool use. Medical diagnosis of hand-arm injuries, Type 1 diabetes, Type 2 diabetes, carpal tunnel syndrome, cervical radiculopathy, ulnar nerve entrapment, Raynaud's disease, rheumatoid arthritis and osteoarthritis (of the hands, wrist, elbow or shoulder). Information relating to respondents use of vibration emitting power tools in the workplace or for domestic use was considered. Specific details of tool use and the type of tools considered was sought. Finally, respondents were asked if they smoked or were ex-smokers.

3. Results

The results of a series of pavement surface surveys and the self-reported symptoms questionnaire survey results are provided in the following sections. The instrumented bicycle pavement surveys were conducted in Summer 2017 and the symptom questionnaire survey was conducted in Spring 2018.

3.1. Instrumented bicycle survey

National cycle network routes were considered for vibration exposure assessment. In conjunction with dedicated cycle path routes, adopted roads were also surveyed to provide a comparison with dedicated off-road cycle path pavement surfaces. Data concerning cyclists' exposure to vibration associated with riding on the shoulder area (1.5m to 2.0m from kerb) on adopted roads was considered. Bus lanes are constructed in Edinburgh as shared space with bicycle traffic.

Kocak and Noble (2010) identified the total length of all cycle paths in the City of Edinburgh as 224 km. They also provided an indication of the split between on-road and off-road cycle path infrastructure as 82 km and 142 km respectively. The present study surveyed 13.682 km of off-road and on-road pavement surfaces, representing 6.1% of the cycle paths identified in 2010. Table 1 provides a summary breakdown of pavement surfaces surveyed.

Table 1 Pavement material type and cycle path category surveyed.

Pavement material	**Road (m)**	**Off-road (m)**	**Total (m)**
Hot rolled asphalt (HRA)	3408	4290	7698
Asphaltic concrete (AC)	0	2392	2392
Cobble setts (CS)	1472	189	1661
Compacted fill material (Cl	0	1099	1099
Monoblock (M)	160	257	417
Concrete pavers (CP)	0	316	316
Concrete (C)	0	99	99
Total survey distance	5040	8642	13682
Total Edinburgh network	82000	142000	224000
% of network surveyed	6.15%	6.09%	6.11%

Vibration exposure data is presented for road and off-road (no motorised vehicles) pavement surfaces. Pavement surfaces surveyed included hot rolled asphalt (HRA), asphaltic concrete (AC), cobble setts (CS), compacted fill (CF), concrete monoblock (M) and concrete pavers (CP). Table 2 shows r.m.s., VDV and $A(8)_t$ data for the off-road pavement survey.

Table 2 Off-road pavement vibration exposure summary (n = 20).

Location and surface category		Distance (m)	Average speed (kph)	Sample time (s)	R.M.S. (ms^{-2})	VDV ($ms^{-1.75}$)	A(8)t (ms^{-2})
NCR754 Union Canal	CS	189	11.33	60.06	12.73	50.24	0.58
Donkey Lane	CF	614	18.31	120.75	9.71	55.42	0.63
A720 Culvert	CF	182	12.22	53.61	6.64	26.90	0.29
A720 Culvert to Railway Bridge	CF	165	11.78	50.44	6.31	24.57	0.26
NCR754 Gilmore Place	CF	138	14.22	34.95	5.35	20.34	0.19
NCR754 Union Canal	AC	621	21.09	105.98	4.65	28.32	0.28
NCR754 Union Canal	AC	610	17.73	123.84	4.13	25.73	0.27
Research Avenue North	HRA	678	18.42	132.49	3.95	29.63	0.27
Station Park	M	257	15.27	60.59	3.88	30.04	0.18
A720 Culvert	CF	99	10.14	35.13	3.77	14.17	0.13
NCR754 Union Canal	AC	517	23.05	80.74	3.72	16.53	0.20
Bankhead Drive	HRA	408	17.38	84.51	3.68	23.15	0.20
NCR754 Union Canal	AC	484	18.26	95.40	3.37	20.98	0.19
North Meadow Walk	HRA	571	26.26	78.28	3.36	15.09	0.18
Middle Meadow Walk	HRA	301	18.86	57.47	3.23	15.15	0.14
NCR754 Union Canal	AC	160	14.93	38.58	3.21	11.48	0.12
Bankhead Drive	HRA	780	19.46	144.27	3.14	17.74	0.22
Carrick Knowe	HRA	1110	23.00	173.75	2.81	17.68	0.22
Station Park	CP	316	17.20	66.16	2.50	13.14	0.12
Stenhouse Drive	HRA	442	22.90	69.48	2.15	10.89	0.11

Table 3 shows r.m.s., VDV and $A(8)_t$ data for the road pavement survey.

Table 3 Road pavement vibration exposure summary (n = 15).

Location and surface category		Distance (m)	Average speed (kph)	Sample time (s)	R.M.S. (ms^{-2})	VDV ($ms^{-1.75}$)	A(8)t (ms^{-2})
High Street	CS	252	21.50	42.20	13.66	46.95	0.52
High Street (P.Square)	CS	159	19.73	29.02	12.85	44.25	0.41
Merchiston Mews	CS	120	13.13	32.90	11.92	39.98	0.40
Napier Road	HRA	283	20.23	50.35	10.41	47.03	0.44
Lawnmarket	CS	839	30.99	97.46	10.11	53.48	0.59
Lawnmarket	CS	102	13.11	28.00	9.03	36.44	0.28
Blantyre Terrace	HRA	282	18.38	55.23	8.45	47.62	0.37
Horne Terrace	HRA	156	17.51	32.08	8.18	32.18	0.27
Merchiston Park	HRA	394	26.03	54.50	7.37	32.99	0.32
Merchiston Avenue	HRA	393	22.83	61.98	7.16	39.54	0.33
East Castle Road	HRA	230	15.52	53.36	5.58	26.29	0.24
Dorset Place	M	160	12.35	46.65	5.53	25.86	0.22
Forrest Road	HRA	354	22.15	57.52	4.51	18.21	0.20
Muir Wood Road	HRA	621	25.19	88.75	3.38	20.47	0.19
Research Avenue North	HRA	695	23.33	107.23	2.77	13.07	0.17

3.2. Symptom questionnaire results

The survey was issued in April 2018 for a period of four weeks. In total, 555 responses were received. The survey respondents mean age was 40 years (SD = 12.42, range 18-77) and the mean number of years cycling was 19 years (SD = 15.41, range 0.6-70). Respondents were asked about their occupation, hobbies and recreational pursuits which may contribute to vibration exposure. The survey also sought information on medical procedures, lifestyle, vibrating tool use (work and domestic) and medical conditions which may contribute to vascular and sensorineural hand-arm vibration exposure symptoms. Of the total response (n = 555) only 24.5% of the respondents (n_s = 136) had a medical history which was suitable for considering cycling to be exclusively responsible for their hand-arm vibration symptoms.

Table 4 Prevalence of self-reported symptoms (n_s=136, screened).

Severity	Blanching	Cold sensation	Stiffness	Swelling	Pain	Tingling	Numbness	Weakness
0	88	68	62	117	73	65	70	105
	64.7%	50.0%	45.6%	86.0%	53.7%	47.8%	51.5%	77.2%
1	45	47	48	18	37	53	57	22
	33.1%	34.6%	35.3%	13.2%	27.2%	39.0%	41.9%	16.2%
2	2	15	20	0	20	16	8	6
	1.5%	11.0%	14.7%	0.0%	14.7%	11.8%	5.9%	4.4%
3	1	4	6	0	6	1	1	3
	0.7%	2.9%	4.4%	0.0%	4.4%	0.7%	0.7%	2.2%
4	0	2	0	0	0	0	0	0
	0.0%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4 shows the prevalence of the self-reported symptoms in participant's hands, wrists, arms and shoulders. A severity index was constructed to examine the prevalence of hand-arm vibration symptoms. For each symptom category, a respondent would be awarded a point for each symptom experienced in the hands, wrists, arms or shoulders, e.g. pain experienced in the hands and wrists would be considered as two points on the severity scale. The authors note the rudimentary nature of the scale and intend to develop the symptom severity measurement process as part of the ongoing research.

Figure 3 shows the screened respondents use of suspension and the relationship with self-reported hand-arm vibration exposure symptoms. In response to, Does your bicycle have suspension?, 109 (80.14%) responded no and 19 (13.97%) responded yes with 8 (5.8%) not providing a response.

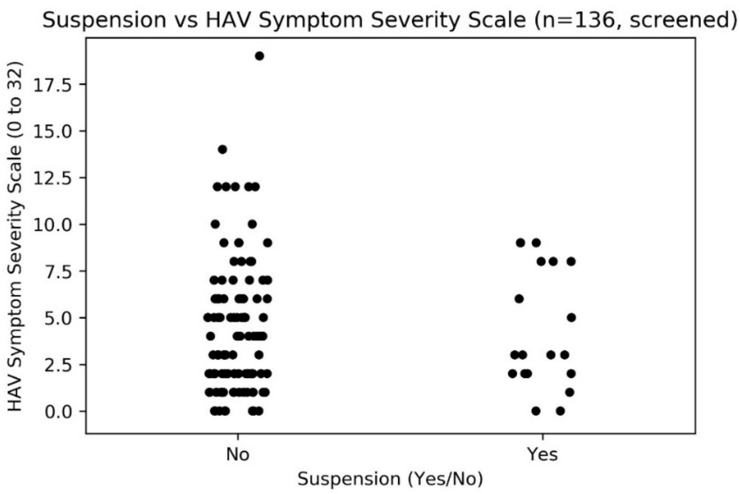

Figure 3 HAV symptoms vs cyclist's use of suspension.

Figure 4 shows the screened respondents number of years cycling versus the self-reported HAV symptom severity scale. Figure 5 shows the reported rider positions and prevalent combinations of rider position reported against the self-reported HAV symptom severity scale.

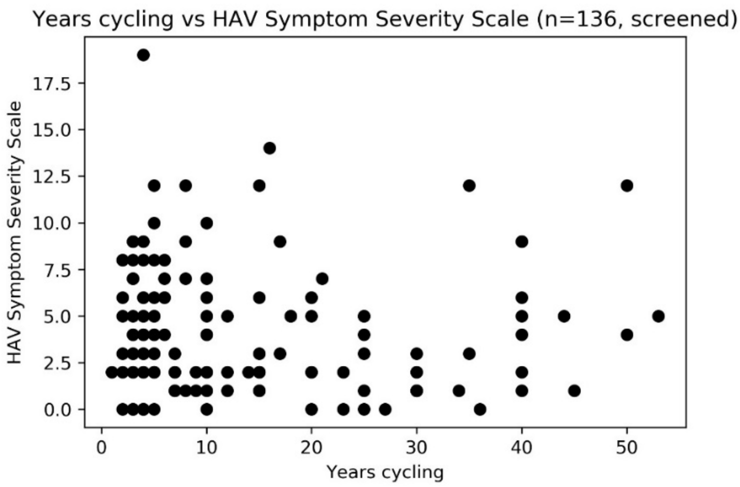

Figure 4 HAV symptom severity vs number years cycling.

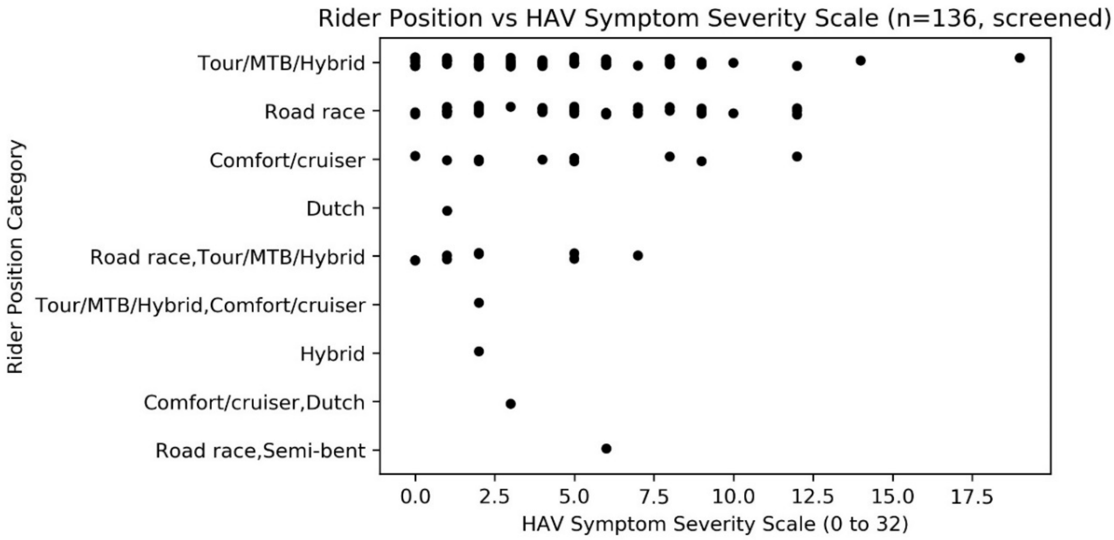

Figure 5 HAV symptom severity versus rider position.

4. Discussion

The data set provides insight into the variation of comfort associated with pavement surface materials used in Edinburgh. Setts are providing considerable vibration exposure in conjunction with defective asphalt and asphaltic concrete surface materials. These surface materials and conditions are providing vibration exposure which may contribute to hand-arm vibration exposure symptoms. The results of the self-reported hand-arm vibration symptoms questionnaire have demonstrated that riders are experiencing symptoms associated with vascular and sensorineural hand arm vibration. The results showed that 33.1 % of screened respondents (n =136) reported blanching, 39.0 % and 41.9% reported tingling sensations in their hands. The use of suspension and the bicycle design type contribute to an increase of self-reported symptom severity. However, the numbers of years cycling appears to have an inverse relationship with reported symptoms. This could be associated with more experienced riders taking measures to reduce vibration exposure, i.e. wearing gloves, adjusting tyre pressure (or tyre type) or avoiding specific routes which require riding over defective pavement surfaces.

Potential limitations of the findings include the accuracy of the information provided by the respondents and that no clinical examination of respondents with high severity score rating was undertaken. The instrumented bicycle data was collected with only one rider and one bicycle type. Future work intends to contact survey participants for instrumented bicycle vibration studies on selected commuter routes in Edinburgh.

5. Conclusions

There is a need to consider the damage caused to cyclists by pavement surface defects as we strive to increase human-powered and electric (reduced emission) vehicles in our cities. Professional cyclists should consider monitoring their vibration exposure and in particular those who cycle in urban areas. Measures for reducing excessive vibration exposure should be sought. For example, gloves, front (and/or rear) suspension, fit adjustments, anti fatigue handlebar grips , appropriate tyre selection and pressure all contribute to improved rider comfort. However, the importance of the pavement surface design and maintenance condition is paramount.

An instrumented bicycle could be used by local authorities when undertaking asset management decisions associated with re-surfacing and maintenance. Future studies intend to examine the relationships between bicycle dynamics, mechanical performance of the bicycle and the tyre interaction with the pavement surface. The collection of objective data concerning cyclists' vibration exposure may contribute to improving pavement specification, asset management practice and a reduced reliance upon direct visual inspection surveys. The results presented provide evidence of self-reported hand-arm vibration exposure symptoms and objective data that quantifies vibration exposure on common pavement surfaces in Edinburgh. It is essential that pavement surface quality is monitored to ensure that there are no public health implications associated with defective inappropriately specified pavement surfaces.

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