Effects of bicycle helmet wearing on accident and injury rates

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Abstract
Bicycle helmet wearing globally has increased over the past 30 years via promotion and in some cases legislation. Various reports have assessed the changes in wearing rates, accidents, injuries and cycling activity levels. A limited number of reports have analysed overall changes in accident risk per kilometres cycled, per hours cycled or in relationship to cycling levels via survey information. A significant number of findings suggest a higher accident/injury rate may result from helmet usage. Accident data from Australia, the United States, Canada, the United Kingdom and New Zealand indicate the accident rate per hour cycled or per miles cycled has increased with greater helmet usage, most likely from a greater proportion and number of upper limb injuries. Consideration is given to why the accident rate may change and if overall safety is improved or reduced by helmet usage.

Introduction

This study considers cyclist participation and hospital injury data in the all-age mandatory jurisdictions of Australia and New Zealand, in Canada where various provinces have all-age or child helmet laws, as well as the United States where child helmets are mandatory in 21 states and with child/adult helmet laws in various town, city and county jurisdictions across the country. These four countries have had the world's longest duration of mandatory all-age or child bicycle helmet laws, whether nationally or in different jurisdictions.

Concerns exist about the effects of bicycle helmet wearing on the accident and injury rates because various studies have reported negative aspects. A USA report found helmet use more than doubled the accident rate compared with no helmet (Porter 2016). Another study demonstrated that helmet use increased the accident/injury rate by 14% (Erke & Elvik 2007) and a New Zealand study detailed a 20% risk increase per hours cycled in association with increased wearing rates (Clarke 2012). At the same time, published reports analysing the influence of bicycle helmets on cyclist injuries generally show a reduction in the proportion of head injuries as well as an increase in arm injuries. Further, injury data is considered in the non-mandatory jurisdiction of the United Kingdom where voluntary helmet wearing has nevertheless been increasing.

Method

The patterns of cyclists' injuries are examined in Australia, New Zealand, Canada and the United States of America where mandatory helmet laws are applied universally or in various areas. Evidence is sourced from both published and unpublished papers and from institutional databases such as the US Centers for Disease Control and Prevention (https://www.cdc.gov/injury/wisqars/nonfatal.html), the Australian Health and Welfare Institute (https://www.aihw.gov.au), the New Zealand Household Travel Survey (http://www.transport.govt.nz/research/travelsurvey/) and the Otago University Injury Prevention Research Unit's Injury Query System (https://psm-dm.otago.ac.nz/niqs/).

Injury data relating to both helmeted and non-helmeted cyclists are examined, as is the overall accident trend in the voluntary jurisdiction of the United Kingdom where helmet use has increased. Possible reasons for changes to the accident rate with helmet usage are considered, together with the rate of accidents for helmeted v non-helmeted cyclists.

Evidence is considered from reports relating to cycling accidents, injuries, helmet use, changes in helmet wearing rates and helmet legislation to assess if trends show an association between helmet use and changes in the cyclist accident rate and/or injury location on the bodies of cyclists. A recent paper considers fatality aspects in some detail[1] and reported, '*The number of cyclist's deaths due to situations not involving motor vehicles appears to increase with helmet use and needs further investigation*'. A summary of these details is provided.

Cyclist injuries vary from minor to fatal, depending on factors such as speed of impact, motor vehicle involvement, type of fall, etc. Numerous reports provide cyclist injury data. The proportion of injuries refers to the distribution of injuries by bicyclist body part injured.

Australia

Whately[2] provided data for all age cyclists from the Australian Capital Territory for 1979 to 1983, detailing the proportion of injury types from accidents stemming from falls and also from those involving motor vehicles. The Victorian Injury Surveillance System (VISS) provided data on children's injuries for 1989[3]. The Monograph 5 report[4] from Queensland provided data following helmet legislation during 1993-2008, mainly relating to road accidents for helmeted v non-helmeted cyclists. McIntosh 2013[5] provides cyclist data for an 18 month period from a major trauma centre in Sydney. Dinh et al[6] provided adult (15 years and older) accident details from an inner Sydney area.

Data extracts from these reports are shown in Table 1 below, which shows the percentage of cyclist injuries sustained as listed in each report and the sample size of each report (not all injuries are listed). The data from Whately relates to main injuries and suggests that a higher proportion of arm fractures result from falls rather than from accidents with motor vehicles, 14% v 8%. The VISS data for children shows 35% of injuries relate to upper limbs. Most child injuries result from falls and a high rate of arm injuries would be expected (11% were hit by motor vehicles, most were falls). The Monograph 5 report details in Table 14 that 28.3% of injuries are to the arm for helmeted v 18.4% for non-helmeted. The McIntosh 2013 study had similar results of 26% v 16%. Monograph 5 reported reduced head injuries for helmet wearers but also mentioned *"Injuries to other body regions did not differ noticeably between helmet wearing riders and non-helmeted riders, except for shoulder and upper limb injuries"*. Helmet wearers have a higher arm injury rate than non-wearers and this suggests they experience a higher rate of falling. With a higher fall rate comes a relatively lower proportion of skull fractures compared with motor vehicle accidents, 9% v 21% and about half the length of hospital stay (Whately 1985). The proportion of skull fractures could be lower for helmeted than non-helmeted cyclists due to head protection and also a higher proportion of falls.

Table 1

	Whately 1985 admissions		VISS 1989	Monograph 5 Table 14		McIntosh et al 2013 Table 2		Dinh et al 2015 Table 3	
	Bic/MV	Bic only	children	Helm.	No Helm.	Helm	No Helm.	Helm	No Helm.
Arm			35	28.3	18.3	26.4	16.0	62	41
Arm fracture	8	14							
Leg			24	29.3	29.6	11.5	8.0	26	22
Leg fracture	19	10							
Head			10	7.4	17.0	24.1	60	40	59
Skull fracture	21	9							
Face			24	9.5	16.0			26	48
Face fracture	7	9							
Concussion	20	29				32.2	50		
IC, inc Conc						34.4	60		
Trunk			6	14.4	12.7	6.9	8.0	20	19
Other fracture	9	5							
Internal injury	8	8							
Other injury	8	16							
SHI/Conc				4.4	9.3				
Neck				9.2	9.2				
Total %	100	100	99	102.5	112.1	135.5	202.0	174	189
Medium age						36.0	21.0	39	31
Average LOS	10.5	4.5							
Alcohol use								2	20
Sample size	**75**	**323**	**916**	**9854**	**2037**	**87**	**50**	**200**	**54**

Note: Bic – bicycle, MV – motor vehicle, Helm – helmeted, No Helm – no helmet, Conc = concussion, IC = intracranial, SHI = Serious head injury (concussion or worse)

Olivier et al[7] reported the change in number of arm injuries following helmet law enforcement in New South Wales, increasing from 660 in 1991 to 1,334 in 2000, a 102.1% increase in the 10 year period. In Western Australia where all age helmet laws were enforced in 1992, the Health Department also reported upper limb fractures increased from 16.4% in 1987-89 to 22.9% in 1990-92 and 28.6% in 1993-95[8]. Meuleners et al 2003[9] data shows that cyclist upper extremity injuries in Western Australia increased from 118 (16.9% of all injury locations) in 1988 to 274 (32.2%) in 1998.

Several reports provide data relating to changes in the accident rate with increased helmet wearing rates. Robinson's 1996 report[10] provided injury data for children from Victoria and New South Wales. In Victoria, the equivalent injury numbers for pre-law levels of cyclist numbers increased 15% from 1990 to 1992, a period during which all age mandatory bicycle helmet legislation was introduced in all Australian jurisdictions. Robinson's data in Table 2 for children in NSW shows the equivalent number of injuries increased from 1,310 (384 head + 926 other injuries) pre law in 1991 to 2,083 (488 head + 1,595 other injuries) in 1993. The relative injury rate proportional to cycling levels increased 59% from 1,310 to 2,083. The relative increase for 'other' injuries was 72% and for 'head' was 27%.

Australia serious injury data

Table 2 below shows in 1990 there were 7,520 hospitalised cyclists compared to 5,048 pedestrians, a ratio of 1.49 to 1. In 2003-04 there were 7,929 hospitalisations for cyclists compared to 3,716 for pedestrians, a ratio of 2.13 to 1[11]. The ratio changes from 1.49 to 2.13 suggests cyclists are more at risk compared with pedestrians, as detailed in the table below. For cycling level estimates refer: Evaluation of Australia's bicycle helmet laws, 2015[12]. Australian Institute of Health and Welfare data[13] show that in 2005/06 there were 4,370 cyclist hospital cases for injury due to road vehicle traffic crashes, of which 43.6% involved the shoulder and upper limbs. There were 2,644 pedestrian cases, of which 15.6% involved the shoulder and upper limbs. In 2015-16, there were 12027 hospitalisations for cyclists compared to 4016 pedestrians, a ratio of 2.99 to 1[14].

Table 2

	1990	2003/04	2005/06	2008/09	2012/13	2015/16
Cyclists	7520	7929	8814	9577	10098	12027
Pedestrians	5048	3715	3779	3686	3823	4016
C/P (actual)	1.49	2.13	2.33	2.60	2.64	2.99
Cycling level % proportional	100	60	59	58	N/A	N/A
Equivalent C/P Best estimate	1.49	3.55	3.95	4.47	N/A	N/A

Notes:

1) Cyclist data for 1990 reported 6,412 hospitalised and was further adjusted in the report for 'Unknowns', where the mode of transport was not known, to total 7,520.

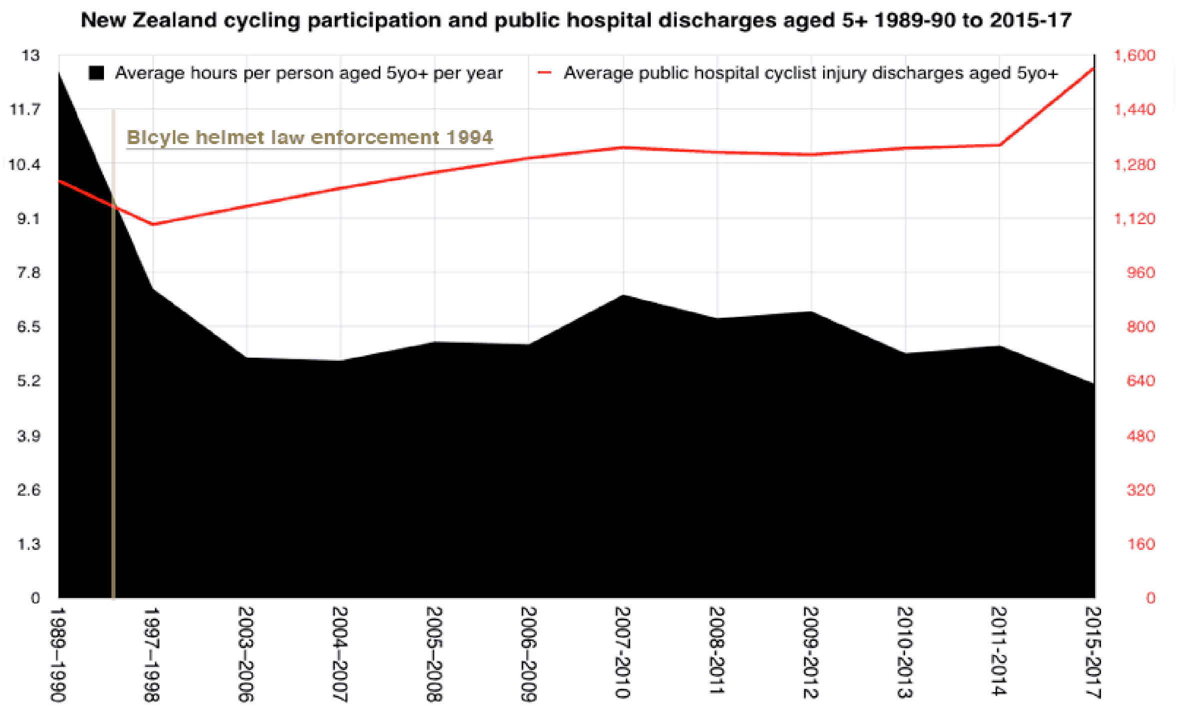
2) Victoria introduced a bicycle helmet law in mid1990 and the 1990 'Cyclist' number of 7,520 may have been higher without the law.

3) The proportion of injuries due to mountain biking may have increased.

4) Table 5 shows cycling to work increased from 2011 to 2016, but still well below 1991 Census ratios. See NCP details in Discussion re declining recreational cyclist participation.

New Zealand

The chart and Table 3 below compare the change in the number of New Zealand public hospital discharges[15] and total hours cycled[16] for people aged 5yrs and older. Relative injury risk is shown for 1989-1990 and subsequent changes are detailed following their helmet law in 1994. The information shows a reduction in average hours cycled per person of between 41.24% and 59.32% and an increased accident/injury risk based on per million hours cycled of between 34.96% and 121.31%. For 5yo+ public hospital discharges from accidents not involving a motor vehicle, the risk of injury per million hours cycled increased 107.2%% from 23.38 in 1989-1990 to 35.85 in 1997-1998 to 48.45 in the 2003/07 period.



Period	1989–1990	1997–1998	2003–2006	2004–2007	2005–2008	2006–2009
Estimated average NZ population aged 5+	3,109,808	3,508,345	3,825,503	3,873,693	3,915,413	3,955,608
Million hours cycling per year	39.200	26.000	22.000	22.000	24.000	24.000
Average hours cycled per person per year	12.61	7.41	5.75	5.68	6.13	6.07
Hours per person % change from 1989-1990		-41.24%	-54.40%	-54.96%	-51.39%	-51.86%
Average public hospital discharge aged 5+	1,229	1,100	1,154	1,207	1,254	1,296
Discharge % change from 1989-1990		-10.50%	-6.1%	-1.79%	+ 2.03%	+ 5.45%
Risk of injury per million hours cycled	31.35	42.31	52.45	54.86	52.25	54.00
Injury risk change from 1989-90		+ 34.96%	+ 67.30%	+ 74.99%	+ 66.67%	+ 72.25%

Period	2007-2010	2008-2011	2009-2012	2010-2013	2011-2014	2015-2017
Estimated average NZ population aged 5+	3,995,025	4,033,723	4,083,538	4,101,355	4,136,205	4,382,327
Million hours cycling per year	29.000	27.000	28.000	24.000	25.000	22.500
Average hours cycled per person per year	7.26	6.69	6.86	5.85	6.04	5.13
Hours per person % change from 1989-1990	-42.43%	-46.95%	-45.60%	-53.61%	-52.10%	-59.32%
Average public hospital discharge aged 5+	1,327	1,313	1,306	1,325	1,334	1561*
Discharge % change from 1989-1990	+ 7.97%	+ 6.83%	+ 6.27%	+ 7.81%	+ 8.54%	+ 27.01%
Risk of injury per million hours cycled	45.76	48.63	46.64	55.21	53.36	69.38
Injury risk change from 1989-90	+ 45.96%	+ 55.12%	+ 48.77%	+ 76.11%	+ 70.21%	+ 121.31%

* 2015-16 only

1989/90 - 2011/14 from http://www.transport.govt.nz/assets/Uploads/Research/Documents/Comparing-travel-modes-2015.pdf

2015-2017 from http://www.transport.govt.nz/assets/Uploads/Research/Documents/Household-Travel-Survey-intro-Dec2017.pdf

Hospital discharge data from Otago University - https://psm-dm.otago.ac.nz/niqs/

Table 3

Table 4 below details cycling levels in million hours per year for the periods shown. For the age group 5-17 total hours cycled reduced from 23 million per year in the 1989/90 period to 7.9 million by 2003/06 period, a drop of 66% and by 2011/14 a reduction of 81%.

	1989/ 90	1997/ 98	2003/ 06	2004/ 07	2005/ 08	2006/ 09	2007/ 10	2008/ 11	2009/ 12	2010/ 13	2011/ 14
5-12 years	9.7	6	4.4	3.7	3.3	2.8	3.4	3.3	2.7	1.8	1.6

13-17 years	13.3	7.6	3.5	3.5	3.4	3.2	3.2	2.9	2.7	2.3	2.8
18 years and over	16.2	12.3	13.8	14.8	17.7	17.8	22.3	21.2	22.2	20.3	20.4
Total (5+)	39.2	26	21.6	21.9	24.3	23.8	28.9	27.4	27.6	24.4	24.8

Table 4 details million hours cycle per year for age groups.

Clarke 2012[17] reported on changes to the injury rate and injuries per million hours of travel following helmet legislation in 1994. The study reported that *"by 2003–07, cyclists had a 20% higher accident rate compared with pre law"*. Referring to the ratio of cyclist to pedestrian injuries per million hours of travel, pre law 1989-91 compared to post law 2004-07, it reported that *"Cyclist's overall injuries more than doubled compared with pedestrians, 5.97 to 12.91, indicating a major reduction in safety."*

Tin Tin et al[18] provided information on the change to 'upper extremity' (injuries per million hours cycled) in Figure 3. It increased from 4.4 to 13.20, indicating a 200% higher rate by 2003/07.

For New Zealand in five year periods from 1989-93 to 2009-13, the number of cyclist deaths not involving a motor vehicle increased from 9 to 10, 12, 16 and 29.

Census data on percentage cycling to work for New Zealand and Australia both show reductions following legislation. Details below in Table 5.

Table 5

	1986	1991	1996	2001	2006	2011	2016
Australia	1.56	1.68	1.50	1.24	1.21	1.24	1.29
New Zealand	5.46	5.39	4.04	3.12	2.52	2.9 (2013 yr)	

Erke and Elvik 2007[19] examined research from Australia and New Zealand and stated that *"There is evidence of increased accident risk per cycling-km for cyclists wearing a helmet. In Australia and New Zealand, the increase is estimated to be around 14 per cent."*

Canada

A Health Report published by Statistics Canada in 2017[20] shows all age cycling in the country declined from 28.7% of the population in 1994/95 to 23.7% in 2013/14, with 12-14yo cycling declining from 67.5% to 52.2% and 15-17yo cycling declining from 56.0% to 45.2%. British Columbia, Ontario, New Brunswick and Nova Scotia introduced all age or under 18yo helmet laws from 1995 to 1997, with four other provinces progressively following suit up to 2015. In 2018 Clarke[21] reported, '*Provinces without all age helmet laws show on average a higher use of bicycles and from 1994/95 to 2013/14 also show a better outcome with more people cycling 42.1% v 29.3%*'.

British Columbia introduced an all age helmet law in 1996. Surveys were conducted in 1995 and 1999 during late July and early August. The survey counts of 3950 v 4246 showed a 7.5% increase, similar to the population increase. In the last week of July and first week of August

1995, Vancouver had 88mm of rain compared with 18mm in 1999[22]. The surveys show the 16-30 age group had reduced counts of cyclists, equating to about five fewer cycling for each extra one wearing a helmet (i.e. 50% of 3950 – wearing rate 47% in 1995 v 35% of 4246 - wearing rate 69% in 1999, 1975 total with 928 wearing v 1486 total with 1025 wearing, 489 fewer cycling v 97 extra wearing). A Vancouver cycling study in 2015 reported young adults aged 16-25 accounted for 4% of bicycle trips and 24% of bicycle/motor vehicles accidents[23] and indicates age grouping and accident data needs to be considered separately.

Nova Scotia introduced an all age helmet law in 1997. Surveys from Halifax[24] 1995/96 to 1998/99 show for the age group 0-19 yrs a drop of 74% in cycling levels - see Table 6 below. The injury data was published by LeBlance et at[25].

Table 6

	1995/96	1997	1998/99
Average number cyclists per day 'A'	88	34	52
% age range 0-19 yrs (number)	24.6% (22)	13.1% (4)	10.7% (5)
All injuries 'B'	416	222	443
Head injuries 'C'	15	3	7
Relative injury risk, B/A	4.72	6.53	8.52
Relative head injury risk C/A	0.17	0.09	0.13

Note - For Canada, the age specific cycling head injury rate for the age group 0-19 per 100,000 population was approximately 51, and 5.1 for the age group 50-64[26]. This suggests a disproportionate reduction in head injuries would result from a reduction in cycling levels for the 0-19 age range.

A helmet law for cyclists aged under 18 was introduced in Alberta, in 2002. Child cycling decreased by 56% from 2000 to 2006 but injuries per cyclist increased following helmet law enforcement in the province of Alberta[27]. From Karkhaneh 2011 report, Table 7 below provides details of the number of cyclists per hour from observational surveys in Alberta (pre-law in 2000, post-law in 2006) and compares these to the numbers treated in emergency rooms (ER) for non-head injuries. For children and teenagers there was a marked reduction in cycling levels and a substantial increase in injuries relative to cycling activity. Safety slightly improved relative to cycling levels for adults without a helmet requirement.

Table 7

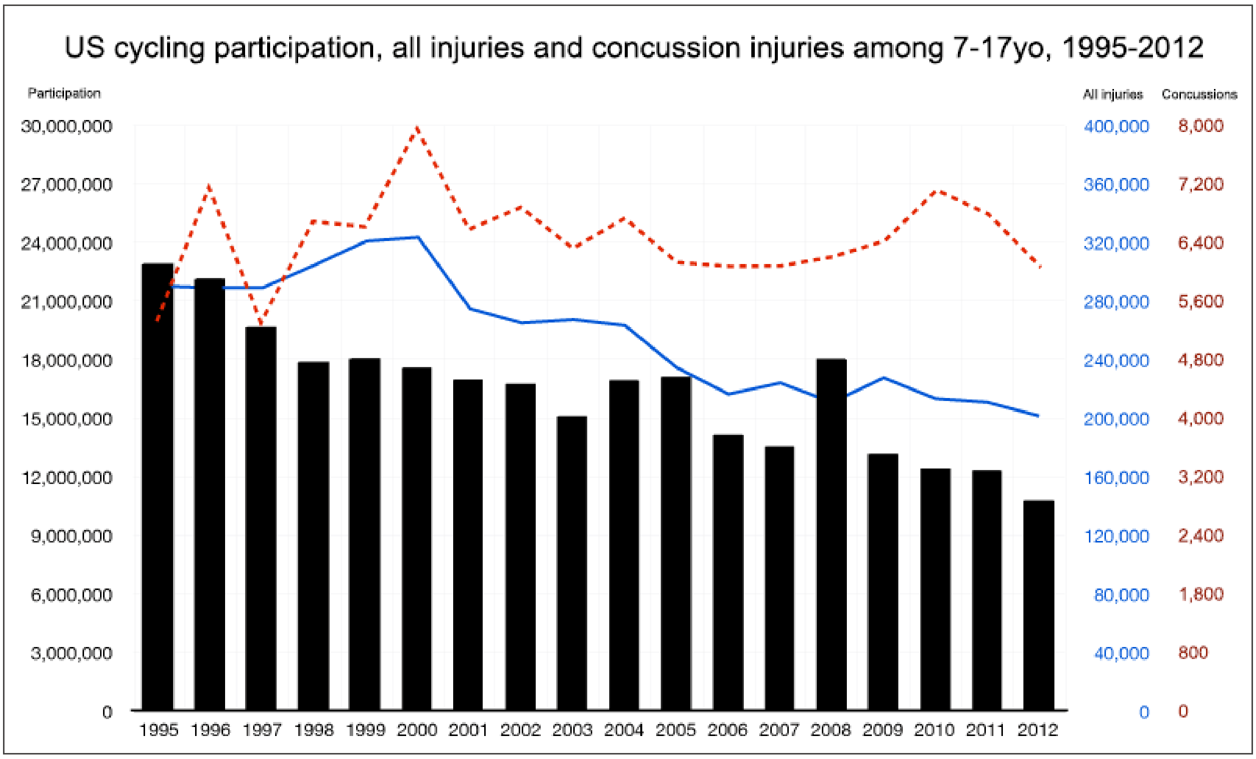
	Cyclists per hour			**Non-head injuries (ER)**			**Change in injuries relative to change in cycling**
	Pre	Post	CRatio	Pre	Post	IRatio	
Children	3.56	1.58	0.44	1676.3	1762.0	1.05	2.37
Teenagers	1.92	1.41	0.73	870.3	1101.0	1.27	1.72
Adults 18+	6.29	7.58	1.21	1846.7	2062.5	1.12	0.93

Clarke 2009[28] reported on helmet laws in Canada comparing injury data for areas with helmet legislation to those without. Overall, the injury outcome adjusted for estimations on cycling levels found provinces without helmet legislation had a better outcome. In 2015 Teschke et al reported: *Helmet legislation was not associated with reduced hospitalisation rates for brain, head, scalp, skull or face injuries, indicating that factors other than helmet laws have more influence on injury rates* [29]. The study focus was on more serious cycling injuries requiring a hospital stay.

For Canada from 2010 -13, road traffic accidents (RTA, involving motor vehicles) recorded 249 cyclist deaths, whereas Statistics Canada recorded 345 (all deaths) a difference of 96, It appears more cyclists are dying from falls than occurred in the early 1990s when the data shows a difference of 7, 363 RTA v 371 SC.

United States of America
Mandatory bicycle helmet laws for youth have been introduced in 21 of the US states and child helmet wearing is high in all jurisdictions - 79% for the under 12 age group[30]. Estimates on cycling levels in the USA vary substantially[31]. Survey details from 1998, indicated more than 17 billion hrs of cycling annually[32], population approximately 270 million, an average of about 63 hrs per capita. The age group 0-15 having the highest levels, mean riding time of 300 hr/yr for those cycling (about 150 hrs per capita).

Cycling participation among 7-17-year-old children in the US declined 23.1% from a 1995-2003 average of 18,593,000 to a 2004-2012 average of 14,296,889, despite a population increase close to 10% during that time[33]. Over the same time period, 7-17yo all-body injuries declined 23.7% from an average 291,970 to 222,869, while concussion injuries among 7-17-year-old cyclists declined 2.1% from a 1995-2003 average of 6,555 to a 2004-2012 average of 6,420, refer Figure



1 below. The relative injury rate increased from 1.27% (291607/22948000) in 1995 to 1.87% (201926/10800000) in 2012, a relative increase of 47%.

Fig 1 Participation – black, Injuries – blue, Concussions- red

The data below in Table 8 compare head, upper body and lower body injury hospital admissions in the US from 1994-2004 to 2005-2015. It is noteworthy that US Census Bureau data show

22,948,000 cyclists aged 7-17yo in 1995 and 13,196,000 in 2009, a 42.5% reduction. Cycling among 18yo+ was 33,360,000 in 1995 and 24,942,000 in 2009, a 25.2% reduction. A 2012 summer survey estimated that 29% of US adults always wear a bike helmet and 56% never wear

7-17yo	1994-2004	2005-2015	% change
Head injuries, concussions	428,125	365,270	-14.7%
Face, upper arm, lower arm, neck, upper trunk, hand, elbow, shoulder	1,228,925	839,586	-31.7%
Lower leg, upper leg, toe, foot	411,086	285,195	-30.6%
18yo+	1994-2004	2005-2015	% change
Head injuries, concussions	228,362	476,305	+108.6%
Face, upper arm, lower arm, neck, upper trunk, hand, elbow, shoulder	859,840	1,204,585	+40.1%
Lower leg, upper leg, toe, foot	184,555	152,169	-17.5%

one. Among children aged 5 to 7 years, 42% always wore a helmet and 31% never wore one while riding[34].

Table 8

It should be noted that Outdoor Industry Association[35] data show US 6-17yo cycling declined from 15,550,000 in 2007 to 12,461,000 in 2015, down 19.9%. US 18yo+ cycling increased from 26,576,000 in 2007 to 30,612,000 in 2015, up 15.2%. The decline in upper body injuries detailed above among 7-17yo is due to an ongoing significant decline in child and teenage bike riding since the 1990s. On the other hand, 18yo+ cycling has been increasing since the 1990s with surveys showing a gradual increase in adult helmet wearing. Concussion, head and upper body injuries have been increasing but lower body injuries have been decreasing when comparing 1994-2004 with 2005-2015.

Research published in the Journal of the American Medical Association[36] found injuries among cyclists aged 18+ in the US increased 28%, hospital admissions increased 120% and head injuries increased 60% from 1998 to 2013.

The Porter 2016[37] report in the US detailed that cyclists wearing helmets had more than twice the odds of suffering an injury than cyclists not wearing helmets. The report's Figure 1 shows the percentage injured among wearers and non wearers in the previous two years. The percentage injured for wearers was 2.81 times higher than for non-wearers.

Carpenter and Stehr reported a reduction in cycling of 4% - 5% occurred due to legislation from 1991 to 2005 for the age group 5-15 years. Chatterji and Markowitz estimated a possible 9% reduction due to helmet laws. The National Sporting Goods Administration suggests a reduction in cycling for the 6-17 age group from 1998 to 2016 of about 40%.

Clarke 2018 examined the cycling fatality risk data and reported an increased risk from death not involving motor vehicles[38]. For the USA, cyclist deaths not involving a motor vehicle in five year periods from 1986-90 to 2011-15 increased from 105 to 114, 150, 209, 258 and 296. Of the 1,024 bicyclist deaths in 2017, 679 died in motor vehicle crashes and 345 in other incidents[39].

United Kingdom
The helmet wearing rate in Great Britain has increased from 2002/03 to 2014/15. In 2002/03 the wearing rate was about 27%, by 2008 about 35%[40] and data from police reported accidents for 2013 shows that 49% of cyclists in known cases were wearing helmets[41]. During this period the accident rate per billion miles cycled increased by approximately 17%. Dodds et al 2018 reported on NHS England data from March 2012 to September 2017 for cyclists older than 15 years, with 61.5% wearing helmets and also having an upper limb injury rate of 61.5% v 47.5% for non-wearers, suggesting helmet wearers having a higher fall off rate (the study did not have data on how the accidents occurred). Injuries to chest, spine and upper and lower limbs averaged 0.89 for non-wearers v 1.43 for wearers (66% higher). Alcohol use was reported as 2.1% for wearers v 15.6% for non-wearers (data from the USA and other countries show other differences in addition to alcohol use may also occur, ref 45). The mortality data reports 1.8% for wearers (76 cases) v 5.6% for non-wearers (143 cases) and 102 cases unknown helmet status. It appears probable that wearers had a higher fall off rate resulting in less severe injuries. Their injury severity score was 12 v 16 for non-wearers.

Great Britain fatality data (DfT Stats19) not involving motor vehicles from 2012 to 2016 shows 22 helmeted v 15 non helmeted, with 38 unknowns[42]. Cyclist fatalities involving motor vehicles were 123 helmeted v 110 non helmeted, with 309 unknowns. Table 9 data below indicates an increase in the fatal and serious injury rate of between 16% and 19% from 2002/03 to 2012/2015. From 2003 to 2016 cycle traffic increased by 25% and the number of serious injuries rose by 48 per cent[43].

Years	2002/03	2004/05	2006/07	2008/09	2010/11	2012/13	2014/15
Average rate	938	937	991	964	1048	1122	1095

Table 9 GB data – fatal and serious accident rate per billion miles cycled[44]

Complimentary evidence
Recent studies have also cast doubt on the reliability of published case control studies and meta-analyses regarding the effectiveness of bicycle helmets. Zeegers 2015[45] states that "*Three cases could be found in the literature with sufficient data to assess both risk ratios and odds ratios: the Netherlands, Victoria (Australia) and Seattle (U.S.A). In all three cases, the problem of overestimation of the effectiveness of the helmet by using odds ratios did occur. The effect ranges from small (+ 8 %) to extremely large (> + 400 %). Contrary to the original claim of these studies, in two out of three cases the risk of getting a head injury proved not to be lower for helmeted cyclists. Moreover, in all three cases the risk of getting a non-head injury proved to be higher for cyclists with a helmet.*"

The Seattle study, Thompson et al[46] claimed, "The use of helmets can reduce the risk of head injury by 85%". The 400% overestimation from the Seattle study shows the degree of error that can occur from using comparisons and odds ratio calculations.

Increased risk
Several possible reasons can be considered that may explain why there is an apparent increased accident/injury risk associated with helmet use. In nearly all cases they are difficult to evaluate and may require further research. Cyclists might believe they are safer with a helmet and take

increased risks, for example in mountain biking events or travelling at higher speeds. Risk Compensation and Bicycle Helmets published by Phillips, Fyhri and Sagberg[47] in 2011 reported *"Our results show increased cycling speed and decreased risk perception in a helmet-on compared to a helmet-off condition among cyclists used to wearing helmets, a finding that is in line with the theory of risk compensation. However, for those cyclists not used to helmets there were no differences in either risk or behaviour between the helmet-off and helmet-on conditions."* These findings support the theory of risk compensation among cyclists in a mandatory helmet environment where they are used to wearing helmets.

Bicycle helmets – A case of risk compensation?[48] was published in 2012 with a survey of 1,504 bicycle owners in Norway finding two sub-populations: one speed happy group who cycle fast and have a lot of equipment including helmets, and one traditional group without much equipment who cycle slowly. In 2016, Gamble and Walker[49] found *"In a controlled study in which a helmet, compared with a baseball cap, was used as the head mount for an eye tracker, participants scored significantly higher on laboratory measures of both risk taking and sensation seeking. This happened despite there being no risk for the helmet to ameliorate and despite it being introduced purely as an eye tracker. The results suggest that unconscious activation of safety-related concepts primes globally increased risk propensity.*

Other explanations for increased accident and injury occurrence for helmeted cyclist may be increased head diameter, impaired vision, impaired hearing, sideways wind shear and forces[50,51], reduced riding stability and loss of "safety in numbers" due to reduced cycling participation following helmet law enforcement. In all-age mandatory bicycle helmet jurisdictions, there is speculation that increased vehicular traffic density might also be a factor as a result of discouraged cyclists instead driving. With regards to "single-cycle non-collision accidents", the contributory factor most frequently attributed by UK police in such accidents was "loss of control" (67% of fatal single-cycle accidents and 44% of serious).[52]

Research has reported cyclists incurring up to 10g forces due to hitting pot holes and lower g forces from road humps, manholes covers and situations where the road/path is not smooth and even. A recent article details g forces from slow cycling speeds incurring up to 6g acceleration forces[53]. A lightweight helmet at 0.25 kg incurring a 4g acceleration would involve a force of about 10N or 2.2 lbs force imperial. In general, helmet use results in extra forces per typical hour cycled and, on some occasions, they may add to problems in maintaining balance. Therefore, the increased "other" rate, mainly falls, is what could be expected from helmet use.

Robinson 1996[54] refers to the Wasserman data that detailed the incidence of cyclists hitting their head/helmet during an 18-month period was *"significantly higher for helmet wearers (8/40 vs 13/476 - i.e. 20% vs 2.7%, p 0.00001)."* A bare head width of approximately 150mm may avoid contact compared to a helmeted head at approximately 200mm wide (Clarke 2007[55]). Assuming the 20% and 2.7% figures are typical, on a yearly average for helmeted and non-helmeted the risk of hitting their helmet or head would be 13.2% and 1.8% respectively. The increased risk of impact for helmeted is about seven times higher. A degree of protection could be expected plus a degree of risk from the extra impacts.

Discussion

There is not universal agreement that bicycle helmets or any other road safety equipment are related to risk compensation, but it is a plausible explanation for the increased ratio of injuries per cyclist in mandatory helmet jurisdictions. We further speculate that parents may allow children to cycle at a younger age with the added protection of a helmet, or children may think they are safer and engage in higher risk cycling. It appears that a combination of factors could result in the higher accident rate, increased risk-taking and factors affecting balance. In the event of an accident, helmet use typically results in higher risk of impact to the helmet than occurs for a bare head.

It has been 29 years since Australia became the first country to mandate all-age bicycle helmets and the evidence is accumulating that such laws have a long-term detrimental impact on cycling participation and the cyclist crash/injury ratio. For example, the National Cycling Participation (NCP) surveys conducted by the Australian government show the total population proportion cycling at least once per week decreased from 18.2% in 2011 to 13.8% in 2019, with annual cycling down from 40.2% to 35.0%[56] Both of these surveys included children cycling in their garden, unlike traditional cycling surveys.

Despite the participation decline, cyclist injuries continued to increase. For example, the NCP survey data show the population proportion who cycle weekly in Victoria declined from 19.9% in 2011 to 13.7% in 2019, yet recently published research[57] shows the number of cyclist major trauma cases hospitalised in the state increased 8% per annum between 2007 and 2015.

We speculate that in the generational timespan of 29 years there is a demographic bulge of baby boomers who have maintained Australian participation levels but are now retiring due to age and not being replaced by younger people who have been discouraged by helmet laws as they grew up. The authors of the NCP 2011-2017 survey reports also state: *"… it is likely that the gradual ageing of the Australian population has contributed to the participation trend, and this demographic shift is likely to exacerbate the challenge of increasing cycling participation in future as the population continues to age. The strong correlation between age and cycling participation means that over time we would expect cycling participation to decline without significant policy intervention or natural cultural shifts."*

In Australia from 1990 to 2014-15, hospital admissions from road accidents decreased for car occupants by 8.4% and for pedestrians by 45.1%, but cyclist admissions increased 7.1%[58]. For Alberta Canada, the change in injuries relative to change in cycling for children is calculated at 237%. From the USA, Porter reports the percentage injured for wearers was 2.81 times higher than for non-wearers.

For New Zealand 5yo+ages, the data in Table 3 above shows the accident rate per million hours increased from 31.35 to 69.38. This related to all accidents involving motor vehicles and for "other" reasons, probably mainly falls and riding into objects or stationary vehicles. For those involving only motor vehicles it did not change very much, roughly eight per million hours to seven per million hours. Accidents due to "other" increased substantially from approximately 23 to 63 per million hours. The 23 accidents per million hours is approximately one per 43,000 hours of cycling on average. If cycling 10 hours per week, this would equate to once in 82 years on average. The disadvantages to helmets and increased risk taking only needs to be minute to increase the accident rate and exceed the expected benefits in a proportion of accidents.

Conclusions

Published studies and research within this paper from jurisdictions with all-age, child and/or adult mandatory helmet jurisdictions consistently suggest reductions in cycling participation when laws are enforced but either no corresponding decrease in hospitalised total injuries or an increase in all-body injuries. Further, there is strong evidence that helmeted cyclists suffer a higher rate of upper body limb injuries than non-wearers, suggesting a higher rate of falls than non-wearers. This may be due to factors such as risk compensation, imbalance caused by the helmet or peripheral vision occasionally obscured by some helmet designs, particularly among cyclists who lower their heads to improve their aerodynamics.

The cause is uncertain but participation and injury data from the countries examined show a negative safety outcome in terms of increased helmet wearing rates and the accident rate per hour and per kilometre cycled. In mandatory helmet jurisdictions, the proportion of head injuries is reduced, although this is partly because the number of upper limb injuries increases.

Confounding factors that are not analysed in this study which may influence participation and injury trends in different countries include changes in cyclist preference for riding on or off road, demographic shifts in cycling participation, varying public compliance with helmet regulations, improved bicycle and motor vehicle safety features, cycle path infrastructure improvements and stricter road traffic laws in different jurisdictions.

Nevertheless, this study presents evidence that helmet use tends to increase the accident/injury rate per cyclist, potentially outweighing any head protection benefits. It reinforces the findings of numerous published studies that mandatory helmet laws reduce cycling participation, which is detrimental to public health and is likely to also increase vehicular traffic if discouraged bike riders alternatively drive a car.

The possible reasons for increased risk of injury per cyclist, particularly upper extremities, appear to be due to increased falls. It appears that helmet use increases the accident rate by more than 40%. This should be the subject of further research to determine why overall accident and injury rates outweigh head injury benefits provided by helmets.

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