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Methodological issues in motorcycle injury epidemiology

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ABSTRACT

Motorcycle riders are over 30 times more likely than car occupants to die in a traffic crash. While this fact is well known, specific issues of methodology in epidemiological motorcycle-injury research have been rarely researched. To facilitate more-valid research on motorcycle injuries, this article evaluates the current state of our knowledge on how we measure the population at risk of injury, completeness of case finding and identification, validity of crash/injury data sources, and completeness of information on important exposures such as alcohol consumption, helmet status, crash severity, and crash speeds, as well as problems of existing injury severity scales and statistical analyses for correlated injury data.

1. Introduction

There has been a rapid increase in exposure to motor-vehicles worldwide, with more than 1 million people are killed on the world's roads (Peden et al., 2004). Among all types of road users, motorcycle riders have the highest risk of fatal and nonfatal injuries. For example, per vehicle mile (or kilometer) of travel (VMT), motorcycle riders in the US are 34 times more likely than car occupants to die in a traffic crash and eight times more likely to be injured (NHTSA, 2007). Methodological issues surrounding epidemiological injury research on motorcycle riders need to be evaluated to avoid biased results leading to incorrect inferences which in turn can easily arise and lead to ineffective intervention programs. This papers reviews problems and needs in the measurement of the population at risk of motorcycle crash injuries, completeness of injury identification, validity of crash/injury data sources, and completeness of information on important exposures such as alcohol consumption, helmet status, crash severity, and crash speeds. Problems of existing injury severity scales and statistical analyses for correlated injury data are also reviewed.

2. Estimating rates or risk of injury

In epidemiology a population at risk should be defined in order to estimate the incidence of injury. Different measures of estimating the population at risk can present totally different risk profiles of motorcycle crash injuries, and a misused measure may misidentify a high-risk (or low-risk) group. The total population in a catchment area over a specified time period is often used to estimate the number of people at risk of injury. The total population most often overestimates the true population at risk of motorcycle crash injuries because not all individuals in a population are exposed to motorcycle riding. The extent of overestimation depends on the proportion of riders in the population; for example, motorcycles consist of 67% of registered motor vehicles in Taiwan (MTC, 2007), while they only account for 2% in the US (NHTSA, 2007). Compared with the total population, the numbers of registered motorcycles, licensed drivers, and vehicle mile of travel (VMT) are somewhat better measures for estimating the true population at risk of motorcycle crash injury because these measures take into account time and actual persons exposed. Nevertheless, injury rates based on the number of registered motorcycles do not allow for direct adjustment for such confounders as age, gender, or other important factors. Even the use of the number of motorcycles registered may still over- or underestimate the population at risk of motorcycle crash injury, because a substantial portion of licensed and unlicensed operators do not own the motorcycle they operate and because older registered motorcycles may no longer be in use. In addition, since unlicensed operators and passengers are not counted in the measure, the number of licensed motorcycle drivers may also underestimate the true population at risk of motorcycle crash injury.

It is customary to use the total number of registered motorcycles as the "population" at risk in a region where a motorcycle crash occurs. However, persons who had crash in one region might not be a resident of that region. For example, Taroko National Park, Hualien

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County, Taiwan attracts many domestic and international visitors who ride a motorcycle from other counties. As a result, neither the population of the County, the number of registered motorcycles in the County, or the number of licensed motorcycle drivers in the County is appropriate. However, if the risk (rate) of motorcycle crash injuries to residents of the County is of interest, motorcycle crashes occurring to visitors need to be excluded from the numerator as well as exclusion of vehicles and persons in the denominator. On the other hand, County residents may have a motorcycle crash injury outside their place of residence. For instance, 36% of residents in Hualin County who died from motorcycle crash injuries died outside the county (Lu et al., 1999). The net effect of these factors on the area-specific injury rates will likely vary across cities, states, and countries.

The use of VMT as the denominator in a rate (or correctly ratio) measure improves the estimation of the true population at risk of motorcycle crash injury; however, some limitations remain. The VMT actually measures the ratio of vehicles that crash among all vehicles (and their miles) in a given time period. The VMT is similar to the use of person-time in conventional epidemiology, in that it assumes a constant level of risk of having a crash per mile over the entire distance of travel. VMT is confounded by the amount of riding time and different road environments; therefore, the crash risk for a given mile in low-mileage groups who had accumulated their mileage on congested city streets is overestimated compared with high-mileage groups who accumulated their mileage on highways (Janke, 1991). To reflect differences in driving patterns and road environments, an index of travel distance divided by travel time (i.e., average speed) was developed (Chipman et al., 1992, 1993). Despite this, concerns on the frequency of riding a motorcycle and road environments such as variations in traffic density remains.

Among measures of the at-risk population, the person-miles of travel (PMT) which takes all riders on the motorcycle into account is theoretically a better measure, even though not all of the problems with the VMT are avoided. The difference in estimating the risk of injury between the PMT and VMT measures remains to be explored particularly when proportions with motorcycles with two or more riders are varied. The PMT is less available in existing surveillance systems and rarely used due to measurement difficulties. Nowadays, with video networks more common on highways, it has become feasible to estimate the true population at risk of injury using the PMT measures.

3. Case identification

There are different severity levels of motorcycle crash injuries, from no injury to fatal injuries. Fatal injuries and those requiring hospitalization are often of more interest to injury researchers because of their more-serious consequences, available injury diagnoses and outcomes, and more-complete data recording. In addition, compared with minor injuries, severe injuries are relatively more easily identified and measured, so they have commonly been used to quantify and describe the health burden of injuries to society (Bach and Wyman, 1986; Bray et al., 1985). Nevertheless, data on mortality and social costs among countries might not be comparable partly because the time interval on defining a motorcycle death varies from country to country. The rules in counting traffic-related deaths varied among countries largely because the definition of time intervals from crash to death in police report. For example, in Australia, France, New Zealand, the UK, and the US, the time interval is 30 days, while in Japan, Spain, and Taiwan, the time interval is only 24 h (de Lapparent, 2006; Jacobs et al., 2000; NHTSA, 2007; Tsai and Hemenway, 1999). In other countries, such as Mexico, only those who die at the scene are counted as a traffic death (Bangdiwala et al., 1985). For comparisons of fatality data based on different reporting time intervals, adjustment factors (i.e., dividing the number of fatalities within a common time interval by the number of fatalities reported in an actual time interval) are needed (Jacobs et al., 2000). For example, in Taiwan the number of motorcycle fatalities within 30 days was estimated by multiplying the number of 24-h fatalities by a factor of 1.62 (Lai et al., 2006). In addition, fatality data from different time intervals can lead to different results on the effectiveness of helmet use or other exposures on motorcycle deaths; for instance, the effectiveness of helmet use was 70% in Taiwan (Keng, 2005) compared to 37% in the US (Deutermann, 2004), since helmets more efficiently prevent brain injuries to motorcycle riders who die within 24 h, if nonhelmeted. The criteria for a hospital admission may also differ across countries and across hospitals in a country, and they often change over time. No study has defined the inclusion criteria for motorcycle and other motor-vehicle injuries requiring hospitalization.

Motorcycle crashes involving minor injuries and those not involving injuries are more difficult to define and identify than those involving severe injuries. Noninjury crashes and minor injury crashes in which riders do not seek medical care are seldom included in motorcycle-injury research, despite some uninjured riders coming to the emergency room for reassurance or insurance requirements. However, there are several reasons to include all severity levels of motorcycle crashes in a study. First, although severe injuries result in tremendous medical costs per case (Bach and Wyman, 1986; Bray et al., 1985), the largest economic cost of motor vehicle crashes results from property-damage-only and minor-injury crashes (those with a score on the AIS of 0 or 1) and such crashes account for 50% of the economic costs of motor-vehicle crashes in the US (Blincoe et al., 2002). Second, preventing collisions involving property damage only and minor injuries can significantly improve the quality of life of individuals, since minor injuries accounted for 88% of quality-adjusted life years lost due to injury in the first 6 months after injury and for 91% over the remaining lifetime (McClure and Douglas, 1996). Third, a representative sample of motorcycle crashes is required to obtain an unbiased result for estimating the incidence and patterns of motorcycle injuries and developing effective prevention programs as well as understanding limitations of police reports and hospital records. Despite police reports and hospital records being traditionally utilized by motorcycle-injury studies, these data sources usually overrepresent severely injured riders (Rutledge and Stutts, 1993). For example, in a population-based cohort study, the ratio of death to nonfatal injury to noninjury was 1:78:191 among young motorcycle riders, and only a few injured riders sought medical care (Lin et al., 2001). The validity of police reports and hospital data for identifying motorcycle injuries is described in the next section.

4. Data sources

Death certificates, hospital records (including trauma registries), and police reports are most commonly used to identify motorcycle injuries. However, none of these sources are mutually exclusive and exhaustive for motorcycle crash injuries.

4.1. Death certificates

The number of motorcycle deaths only on death certificates was often less than that on police reports (Braddock et al., 1992; Lapidus et al., 1994; Sosin et al., 1990). The proportion of unspecified injuries on death certificates (e.g., codes of the International Classification of Disease, Ninth Revision (ICD-9): 958.4, 958.8, 959.8, and 959.9) is often high, while certain anatomic injuries (e.g., abdominal, head, and spinal injuries) and important exposures (e.g., alcohol drinking) are underestimated (Braddock et al., 1992; Hodgson et al., 2000; Lapidus et al., 1994; Moyer et al., 1989; Pollock et al., 1987; Sosin et al., 1990). For instance, compared with medical examiner's reports in California, the proportion of unspecified injuries on death certificates was more than 60%, and the reporting sensitivity was only 47% for head injuries and less than 3% for chest and extremity injuries (Romano and McLoughlin, 1992). Up to a half of death certificates may have errors in the diagnosis and external cause of injury (Lapidus et al., 1994). With differential errors in risk subgroups, data of death certificates may lead to incorrect results and inferences, such as a failure to detect a significant relationship between head injuries and helmet use due to low reporting sensitivity for head injury and its difference between helmeted and nonhelmeted riders (Romano and McLoughlin, 1992). Furthermore, regional differences in the quality of death certificates such as the use of unspecified codes may also bias mortality rates of motorcycle injury across regions (Pollock et al., 1987). Training in procedures for certifiers and computerizing death certificate coding systems which can be linked to medical examiner's records can improve the accuracy and quality of death certificates for use in motorcycle-injury research. In addition, physicians should be made aware that certification is not merely a bureaucratic formality but also is a requirement for building up epidemiological data (D'Amico et al., 1999).

4.2. Hospital records

Hospital records such as discharge data provide excellent information on severe as well as moderate nonfatal injuries; however, they represent only 4% of all nonfatal injuries (Rice and MacKenzie, 1989). Several limitations exist in hospital data. First, injured riders treated in hospitals might not have a risk of motorcycle crashes and injuries similar to that of those involved in motorcycle crash injuries. Hospital records commonly exclude on-scene deaths as well as most less-serious injuries, and a few deaths related to motorcycle injuries may occur after hospital discharge (Mullins et al., 1998). About 70% of hospital admissions and fewer than 40% of emergency room visits were reported by the police (Cercarelli et al., 1996; Harris, 1990; Maas and Harris, 1984; Rosman and Knuiman, 1994). Additionally, they do not include information on crash characteristics or road environments. As a result, hospital data are not appropriate to determine risk or protective factors for motorcycle crashes and injuries. Second, admission criteria may differ across hospitals, change over time, or depend on certain selective factors such as age and ethnicity (Dhillon et al., 2001; Rosman and Knuiman, 1994). Motorcycle riders whose crashes occurred in rural areas, local/off roads were less likely to be hospitalized (Meuleners et al., 2007). Third, hospital discharge data based on the ICD codes of external cause and nature of injury (i.e., E and N codes) provide an important source for estimating the number and incidence of motorcycle injuries; however, they often have a substantial part of incomplete or missing data and repeated admissions for the same injury event. For example, about one-half of hospital discharges in New Zealand were incompletely specified, particularly as to injury mechanisms, activity, and place of injury occurrence (Langley et al., 2007), and 11.7% of all hospitalized, motor-vehicle injuries in Australia were repeated admissions (Boufous and Williamson, 2003). Therefore, the incidence of motorcycle crash injuries are inaccurately estimated by hospital discharge data because of the incomplete information and repeat admissions, as well as variations in the definition of injury, quality of injury-related coding, and identification of the population at risk (Lawrence et al., 2007; Rice and MacKenzie, 1989; Smith and Barss, 1991).

4.3. Police reports

Data from police reports such as the US Fatality Analysis Reporting System (FARS) provides information on features of the crash and the road environment as well as vehicle information such as the make, model, and stroke volume but lack detailed information on patterns and severity levels of injury (NHTSA, 2007). Nevertheless, compared with injuries to other motor-vehicle occupants, motorcycle injuries consistently are less likely to be reported by the police (Amoros et al., 2006; Aptel et al., 1999; Loo and Tsui, 2007; Lopez et al., 2000; Rosman and Knuiman, 1994); a telephone survey even found that only one-third of motorcycle injuries were recorded by the police (Harris, 1990). Police may underreport crashes involving single vehicles and unlicensed riders (Lopez et al., 2000), and data on injuries occurring in remote areas where police presence is minimal are substantially never submitted (Smith and Barss, 1991). Compared with hospital records and death certificates, the underreporting is also associated with the motorcycle rider's age (<16 years old), social characteristics (non-residents), time (night arrivals at the emergency department), alcohol consumption (with higher levels of blood alcohol concentration, BAC), and injury severity (less-severe injuries) (Aptel et al., 1999; Barancik and Fife, 1985; Grossman et al., 1996).

Police reports may also lack precise information on the injury diagnosis and severity. Policemen usually correctly identify riders as either killed or uninjured, but the severity levels of nonfatal injury are often over- or underestimated (Aptel et al., 1999; Cercarelli et al., 1996; Sciortino et al., 2005). Often, injuries without outward signs are missed by police, and of these vehicle occupants coded by police as having no injury, two-thirds were rated by medical personnel as having minor or moderate injuries (Farmer, 2003).

4.4. Combination of data sources

Combining data from death certificates, hospital records, police reports, and medical examiner's reports may provide more-complete and less-biased information to assist in prioritization of injury prevention programs and for identifying methods of prevention (Cryer et al., 2001). In many situations, a unique identifier or groups of elements that uniquely identify a given person or event will not be available, the probabilistic record linkage has been applied (Clarke, 2004; Howe, 1998). In the record linkage, the definitions of a motorcycle crash/injury and its severity across data sources often are different and need to be standardized. Female drivers and those with less-severe injuries are consistently reported to have lower linkage rates compared with their counterparts (Boufous and Williamson, 2003; Cryer et al., 2001; Lopez et al., 2000).

Alternatively, capture–recapture methods can be applied to model data from two or more sources to estimate the number of all injuries in a defined population; in addition, the potential dependence between data sources, the extent of under-ascertainment in the population, and the efficiency of individual data sources can be estimated as well (LaPorte et al., 1995). These methods were also applied to estimate the incidence or prevalence of head and spinal cord injuries (Chiu et al., 1993), even though they have not been used for motorcycle injuries. Under the capture–recapture analysis for modeling multiple sources, there are several assumptions: independence between data sources, all identified cases being in the population, equal efficiency of any source for all members in the population, and the constant efficiency of any source over the study period (McCarthy et al., 1993). Often, the first assumption is violated in that the processes of data collection among crash/injury data sources are not independent from one another and resulting positive dependence can lead to an underestimation of the true number (Morrison and Stone, 2000; Papoz et al., 1996). It should be also noted that data on most minor injuries or noninjuries remain unavailable and underestimated in the combined data of these sources.

5. Exposure measurement

Accurately measuring contributing factors to motorcycle crash injuries such as alcohol consumption, helmet use, crash severity, and crash speeds is essential if we are to fully understand the dynamics of crashes and the resulting injuries. These factors are often correlated and vulnerable to confounding with each other (Beirness and Simpson, 1988; Boyce and Geller, 2002; Jessor, 1987; Jonah et al., 2001) and if a substantial proportion of information on these factors is incorrect or missing entirely, biased results and incorrect inferences may easily arise. For example, intoxicated riders who are used not to wear a helmet may have a higher risk of head injuries than sober riders who usually wear a helmet. However, if the effect of helmet status is removed, the higher risk of head injuries among intoxicated riders disappears. Furthermore, the direction and magnitude of the potential bias due to missing data are rarely further examined.

5.1. Alcohol consumption

The BAC values are frequently obtained soon after a motorcycle crash. The BAC may be under- or overestimated by time delays, intravenous treatment, loss of blood, and shock (Öström et al., 1992), and thus where allowable by law a blood sample should be taken from a motorcycle rider involved in a crash as quickly as possible to avoid an erroneous measurement. The proportion of motorcycle deaths with an unknown alcohol status was higher than those with a known status (NHTSA, 2007). Missing data on alcohol use in injured motorcycle drivers do not occur randomly. Males and seriously injured drivers in motorcycle crashes are more likely to have blood alcohol tests (Evans, 2004; Öström et al., 1992; Paulozzi and Patel, 2004; Peek-Asa and Kraus, 1996), and all riders who consume alcohol also engage in other risk-taking behaviors such as speeding and not wearing a helmet (Lin et al., 2003a; Rutter and Quine, 1996). If uninjured or mildly injured riders are tested only due to external signs of alcohol use, speeding, or being helmeted and those seriously injured are consistently tested, the differential measurement can lead to an underestimation of the association between alcohol use and injury severity. In addition, acute alcohol involvement may cause erroneous ratings on initial assessments of injury severity, particularly on mild or moderate traumatic brain injuries (Waller, 1988).

Some issues related to alcohol use remain unanswered. First, relative to other motor-vehicle drivers, motorcycle riders are more vulnerable to alcohol's effects on balance, motor coordination, and judgment (Colburn et al., 1993; Sun et al., 1998). Nevertheless, a lower legal limit of BAC for motorcycle operators has not been established. Second, the effect of alcohol use on the incidence and severity levels of motorcycle injuries are usually not differentiated; however, it is better to do so to effectively target alcohol-related intervention programs. Finally, among sobriety checkpoints, enforcement of BAC laws, zero tolerance, mandatory jail terms for a first conviction, and administrative license revocation, only the enforcement of BAC laws has been shown to be effective in reducing alcohol-related motorcycle deaths (Villaveces et al., 2003). However, the effects of other alcohol-related interventions such a minimal legal age, increased excise taxes on alcohol, and responsible beverage service on motorcycle crash injuries have not been examined.

5.2. Helmet use

Helmets have been shown to reduce the risk of motorcycle deaths by 28–29% during the period of 1972–1987 (Evans and Frick, 1988; Wilson, 1989). The effectiveness increased to 37% during 1993–2002 possibly due to improvements in helmet design and materials (Deutermann, 2004). However, helmet types and fastening status are rarely measured, and differences in their effectiveness at reducing head injuries have been little explored (Tsai et al., 1995). In addition, studies of the effectiveness of helmet use laws on motorcycle deaths have inconsistent results (Branas and Knudson, 2001; Houston and Richardson, 2007; Morris, 2006; Sass and Zimmerman, 2000). The actual rate of helmet use in riders that may confound the result were not controlled for. Adequate statistical models, described in Section 7, for simultaneously detecting the global-level effect of the helmet use laws and individual-level effect of helmet use on motorcycle deaths may help clarify the inconsistence. In police reports or hospital records, it is often to report a substantial proportion of riders, as much as 48%, with unknown helmet status (Karlson and Quade, 1994; Murdock and Waxman, 1991; Orsay et al., 1995; Rowland et al., 1996; Rutledge and Stutts, 1993; Shankar et al., 1992). However, in regions with mandatory helmet use, the proportion of helmeted riders is frequently above 90%. It is unclear if the missing information is associated with severity levels of injury and wearing status. In a case-control study in which helmet status was validated, the false negative rate (32%) was higher than the rate of false positives (13%) (Lin et al., 2004a).

5.3. Crash severity

Crash severity is seldom controlled for in studies of helmet use and head injuries. Without controlling for this, these studies implicitly assume a similar distribution of crash severities between helmeted and nonhelmeted riders; often this assumption is violated (Hurt et al., 1981; Prasad, 1990). There are no standardized measures of severity for motorcycle crashes; nonetheless, five measures have been applied. A three-level scale of crash severity is commonly used in police reports: "property-damage only" (no injury), "injury" (incapacitating, evident), and "fatal" (killed) (NHTSA, 2007). When the crash severity of an injured rider is unknown, the level of "injury" will be assigned by default. This measure is strongly judged by the severity level of injury to a rider, and this may cause differential misclassification of crash severity. The approximate change in velocity (i.e., delta-V) during a crash, often used by the National Accident Sampling System (NASS) (NHTSA, 2002), can be computed by crash reconstruction algorithms based on the estimation of the absorbed crush energy by the vehicle from the post-crash measurements of the vehicle deformation. Although the delta-V for crash severity has been well-validated by road engineers (Prasad, 1990; MacWilliam and Schneider, 2001), it is seldom reported in epidemiological research. A modification to the Injury Severity Score (ISS) that calculates only injuries to body regions other than the head has been more frequently applied in epidemiological research (Rutledge and Stutts, 1993). This index, which implicitly assumes that the occurrence of injuries to body regions other than the head is independent on the incidence of head injuries or the use of a helmet, might not be valid. Another measure of crash severity, repair costs of motorcycle damage (Lin et al., 2001), which can be affected by social and economic factors; for instance, given the same vehicle damage, the repair cost would be more expensive in urban areas than in rural areas. Finally, the use of collision type (Gabella et al., 1995) might not be able to discriminate severity levels among various collision objects or among single-vehicle crashes. For epidemiological research with a large sample size, the modification to the ISS and repair costs of motorcycle damage are more convenient to be collected than the delta-V and they can have a better ability to discriminate severity of motorcycle crashes than the three-level scale of police report and the collision type.

5.4. Crash speeds

The crash speed at the time of impact contributes to the severity of motorcycle crashes and injuries as with all other types of motor-vehicle crashes (Lin et al., 2003; NHTSA, 2007; Shibata and Fukuda, 1994). Nevertheless, insufficient evidence is available for crash speeds to be significantly associated with the occurrence of motorcycle crashes, probably because noninjuries and minor injuries that may occur at low or moderate speeds are seldom included in such studies. Road engineers and police determine crash speeds using information on vehicle damage, post-crash trajectories, and skid marks at the scene (Hurt et al., 1981; Richter et al., 2001); however, the speed analysis for an in-depth investigation is laborious, costly, and time-consuming. Crash speeds have seldom been reported in epidemiological studies due to technical difficulties; if any, they are recalled (erroneously) by riders who survived a crash (Lin et al., 2001), are signified by posted speed limits on the road where the crash occurred (Branas and Knudson, 2001), or are indicated by vehicle damage (Obenski and Hill, 1997). However, riders may consciously report slower crash speeds due to legal concerns; the actual speed at a crash may heterogeneously exceed the posted speed limit by 5, 20, or even 40 mph; and the ability of emergency physicians to correlate between vehicle damage and crash speeds is poor (Ros et al., 1995). Event data recorders (EDRs) are devices installed in many automobiles and trucks to record information on vehicle crashes. Similar to the black box on airplanes, information from EDRs can be collected after a crash and analyzed to help determine what the vehicles were doing before, during, and after the crash. Installing such devices in motorcycles is promising for collecting of speed and other characteristics at the time of a crash.

6. Measurement of injury severity

The Abbreviated Injury Scale (AIS) is the most common measure to assign a severity level to each injury. The AIS ranks injuries on a scale of 1–6, with 1 representing minor injuries and 6 representing untreatable injuries (AAAM, 2005). The Maximum AIS (MAIS), the highest single AIS score in persons with multiple injuries and neglecting the synergistic effect among multiple anatomic injuries, has been used to indicate overall severity (AAAM, 2005), but it was not linearly correlated with mortality (O'Neill et al., 1979). A 5-level KABCO scale, applied by the NASS/CDS for measuring overall injury severity, codes fatal injuries as "K", incapacitating injuries as "A", nonincapacitating injuries as "B", possible but nonevident injuries as "C", and no injuries as "O" (NHTSA, 2002). As most commonly used, the ISS which groups the nine AIS body regions into six (head/neck, face, chest, abdominal/pelvic contents, extremities/pelvic girdle, and external) was developed to summarize multiple injuries (Baker et al., 1974). The ISS scores are calculated as the sum of the squares of the highest AIS scores for the three most severely injured body regions, with a range of from 1 to 75. Nevertheless, compared with other injury severity scales of CRAMS (circulation, respiration, abdomen, motor, speech), PHI (prehospital index), RTI (revised trauma index), and RTS (revised trauma score), the ISS had the lowest performance level in the prediction of mortality (Lett et al., 1995). A New Injury Severity Score (NISS) selects the three most severe injuries, including those in the same region, to compute the sum of the squares (Osler et al., 1997). Although the NISS is more predictive of mortality and other clinical outcomes than the ISS (Balogh et al., 2003; Brenneman et al., 1998; Frankema et al., 2005; Lavioe et al., 2005), its comparisons with other severity scales across different datasets with a variety of mortality rate are needed.

Data on these severity scales are often analyzed as if they were interval or ratio scales. For instance, when comparing AIS scores, the difference between 1 and 2 (moderate injury) is assumed to be equal to the difference between 4 (severe, life threatening injury) and 5 (critical injury) or between 5 and 6 (unsurvivable injuries). However, the measurement of these severity scales is ordinal, and thus calculating the mean and standard deviation and changes of these injury severity scores may lead to incorrect inferences. For instance, a medical progression of ISS scores from 16 to 4 is surely not the same as progression from 29 to 17. Moreover, it is still unclear if the same AIS (or ISS) scores from different body regions are comparable; for example, does an AIS 3 score of the lower extremity indicate the same damage as an AIS 3 score of the head? Measurement problems of these injury severity scales may be overcome potentially by Rasch models that estimate the intervals between ordinal items (e.g., AIS scores from different injured body regions) from a single underlying construct (e.g., injury severity) on a logit scale to approximate interval values (Wright and Linacre, 1989; Wright and Masters, 1982). However, no study using the Rasch models has been used to calibrate these injury severity scales.

The AIS, ISS and many other existing severity scales cannot discriminate severity levels among less-severe injuries, probably due to their development being based on hospital-based injured patients. The insensitivity of these severity scales to the minor levels of injury leads to a neglect of identifying factors affecting occurrence, prognosis and prevention of less-severe injuries. More-sensitive scales to discriminate severity levels among less-severe injuries are particularly needed for epidemiological studies in communities in that minor injuries account for more than 90% of motorcycle crashes (Lin et al., 2001).

7. Analysis for correlated injury data

It is common for a motorcycle rider to have multiple injuries in a crash, for recurrent injuries to occur to a motorcycle rider over time, and to have multiple injured riders in a crash. For example, 10% of young riders in Taiwan had more than one motorcycle crashes and 2.8% had more than two crashes over a 20-month study period. These injuries are often treated as independent events, or only the first injury of recurrent crashes is counted, or only one of several injured riders in a crash is included. However, these injury events within the same individual, the same crash, and the same community are correlated (Williamson et al., 1996). With correlated injury data, traditional statistical models may result in inefficient estimates of regression parameters and inconsistent estimates of precision (Zeger and Liang, 1992). For example, the standard Poisson sampling distributions which assume motorcycle deaths occur at random within a state or in the same crash tended to underestimate the expected variability of standardized fatality rates (Morris, 2006; Norvell and Cummings, 2002), and thus covariates may be incorrectly identified as significant predictors in some circumstances (Williamson et al., 1996).

Adequate statistical models which account for the correlation, such as generalized estimating equations (GEEs) (Liang and Zeger, 1986; Zeger and Liang, 1986), random-effects models (Laird and Ware, 1982), and transitional or Markov models (Cox, 1970; Muenz and Rubinstein, 1985), have been applied to motorcycle-injury studies (Branas and Knudson, 2001; Lin et al., 2003a,b, 2004; Morris, 2006; Villaveces et al., 2003). While using the GEE method, inferences of the estimates of regression coefficients are asymptotically valid, even when the correlation coefficient is misspecified, the random-effects model allows estimation of individual paths of injury occurrence and the average of these paths (Zeger and Liang, 1992). For transitional models, the regression coefficients can be interpreted as the effects of covariates on the risk of a motorcycle injury adjusted for the past history of motorcycle injury (Lin et al., 2003a). On the other hand, selection of a statistical model appropriate for a correlated injury outcome of study is also important. For example, studies have produced inconsistent results on the relationship of universal helmet laws and motorcycle deaths (Branas and Knudson, 2001; Houston and Richardson, 2007; Morris, 2006; Sass and Zimmerman, 2000), and the inconsistence is partly attributable to the differences in the selection of the analytical model. Compared with other models, random-effects models should be more valid in detecting the effect of helmet use laws (i.e., global-level exposure), since they can adjust for individual's helmet use by motorcycle rider (i.e., individual-level exposure) and even interactions of helmet use and helmet use laws (i.e., cross-level interactions).

When more than two levels of motorcycle injuries are the outcome variable, proportional odds models (McCullagh, 1980) in which the correlation of multiple crashes involving the same individual is adjusted for by the GEE can be applied (Lipsitz et al., 1994; Lin et al., 2003b). Statistical methodologies for combining both recurrence and severity data in jointly modeling the number of events and a vector of correlated severity measures using the GEE have recently been developed (Albert et al., 1997). When the time to the event is of study interest, several generalized proportional hazards, including Andersen and Gill (1982), Prentice, Williams, and Peterson gap time and total time (Prentice et al., 1981), and Wei, Lin, and Weissfeld methods (Wei et al., 1989), can handle the recurrence of motorcycle injuries. Furthermore, the choice of a time-scale (e.g., age, time since the baseline assessment, or calendar time) in the proportional hazards model is associated with whether there are unbiased regression coefficients (Korn et al., 1997). When seasonal effects on the occurrence of motorcycle crashes are a particular concern, a calendar time-scale rather than time since the baseline assessment is more valid (Lin et al., 2003a).

8. Summary

Among measures of the population at risk of injury, the use of the total population can be misleading and the person-miles of travel is the most appropriate. Although fatal and severe injuries are most commonly studied, prevention of minor injuries is important in reducing risk factors, lowering economic costs, and improving the quality of life. Three data sources of information (death certificates, hospital records, and police reports) are most commonly used to identify motorcycle injuries; however, none of these sources includes all motorcycle injuries. The capture–recapture method can help estimate more-complete and -valid information on the number of motorcycle injuries, if model assumptions are not violated. Missing data on and imprecise measurements of important exposures such as alcohol consumption, helmet use, crash severity, and crash speeds can potentially result in biased results leading to incorrect inferences. Existing injury severity scales, based on hospitalized patients, are not designed for assessing severity levels among less-severe injuries. In addition, it is inappropriate to calculate the means, perform statistical testing, and directly interpret score changes in severity scales based on their ordinal measurements. More-valid statistical methods for correlated motorcycle crashes and injuries such as generalized estimating equations, random-effects models, and transitional models can be employed to increase the validity and efficiency of estimating parameters of interest. Furthermore, selection of a statistical model appropriate for the correlated injury outcome is also important to obtain more valid results and inferences.

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