Risk of horses falling in the Grand National

Analysis of past tumbles in this gruelling steeplechase points to ways of making it safer.

As in other competitive sports, the famous Grand National steeplechase, which is held at Aintree in the United Kingdom and is watched by 600 million people worldwide[1], sometimes results in injury. By analysing data from the past 15 Grand National races (consisting of 560 starts by horses), we are able to identify several factors that are significantly associated with failure to complete the race: no previous experience of the course and its unique obstacles, unfavourable ground conditions (too soft or too hard), a large number of runners, and the length of the odds ('starting price'). We also find that there is an increased risk of falling at the first fence and at the jump known as Becher's Brook, which has a ditch on the landing side. Our findings indicate ways in which the Grand National could be made safer for horses and illustrate how epidemiological analysis might contribute to preventing injury in competitive sport.

The race comprises 30 obstacles over a distance of 4.5 miles (7.2 km) (Fig. 1). We used multivariable models to identify the variables associated with non-completion and with falling (see supplementary information).

The probability of remaining in the race (Fig. 2a) shows a marked decline at fence 1, followed by a steady decline throughout the rest of the race. Non-completion is further subdivided into different types (Fig. 2b), and demonstrates an increased rate of falling and of horses being 'brought down' early in the race by interference from another falling horse, followed by a higher rate of refusals and horses 'pulling up' (jockey-initiated withdrawal from the race).

Compared with other plain fences (no ditch), the first fence is almost seven times more likely to result in a fall (odds ratio, 6.8; 95% confidence interval, 4.6, 10.0). Becher's Brook (odds ratio, 4.7; 95% CI, 3.2, 7.1), open-ditch fences (odds ratio, 2.4; 95% CI, 1.6, 3.6), Canal Turn (odds ratio, 2.1; 95% CI, 1.2, 3.6) and The Chair (odds ratio, 2.3; 95% CI, 1.1, 4.6) all confer a significantly increased risk of falling.

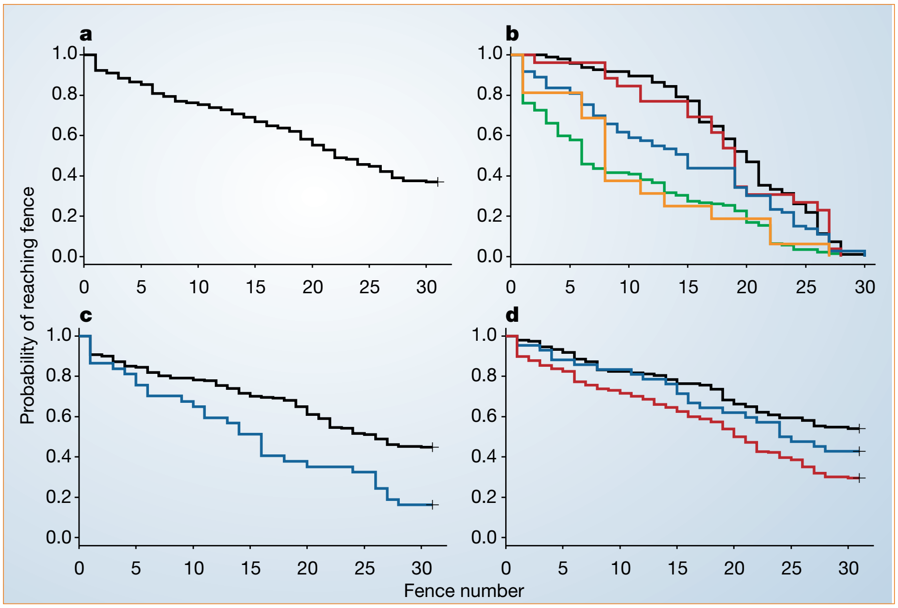

Figure 2 Patterns of non-completion of the Grand National during the past 15 races. **a,** Cumulative probability of reaching each fence for all 560 starters. **b,** Probability of reaching each fence is categorized by non-completion type: green, fell; black, pulled up; red, refused; blue, unseated; orange, brought down. **c,** Probability of reaching each fence categorized by ground condition ('going'): black, good or good-to-soft; blue, soft or heavy. **d,** Probability of reaching each fence categorized by previous experience on the Grand National course: black, raced, no falls; blue, raced and fell; red, never raced.

Ground classified as 'soft' or 'heavy' resulted in a significantly higher rate of non-completion (hazard ratio, 2.05; 95% CI, 1.32, 3.17) compared with all other types. The model predicts that only 18% of runners will complete when the 'going' is soft or heavy (Fig. 2c). Horses that had never raced on the course were twice as likely not to complete it (hazard ratio, 2.0; 95% CI, 1.52, 2.63) as horses that had had previous experience without a fall (Fig. 2d); this relationship remained after adjusting for age. The number of runners in the race was associated with non-completion (hazard ratio, 1.09 per runner; 95% CI, 1.01, 1.13), as was the 'starting-price multiplier' (the inverse of starting price; hazard ratio, 1.004; 95% CI, 1.002, 1.006) — the longer the odds, the greater the probability of non-completion.

Falling or unseating of the jockey as a result of a jumping error is the outcome most likely to result in injury[2–4]. Horses with no previous experience on the course were at increased risk of falling and of losing their rider (hazard ratio, 2.6; 95% CI, 1.80, 3.87). Good-to-soft ground was associated with a significantly decreased risk of falling relative to good ground (hazard ratio, 0.41; 95% CI, 0.21, 0.78). The number of runners in the race (hazard ratio, 1.08; 95% CI, 1.01, 1.17) and the starting-price multiplier (hazard ratio, 1.003; 95% CI, 1.001, 1.005) were also significantly associated with a risk of falling.

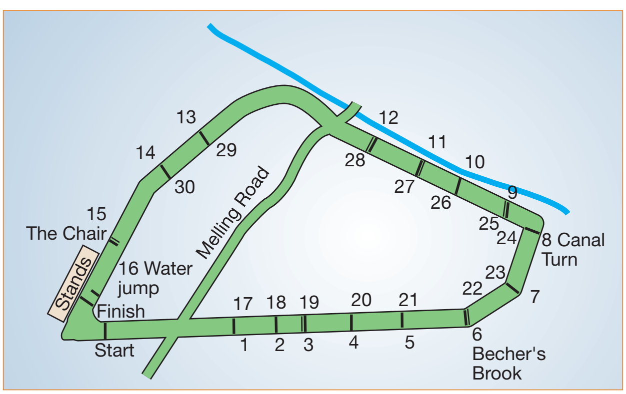

Figure 1 Layout of the course of the Grand National. The race comprises almost two complete circuits of this course. The 30 obstacles (numbered) jumped during the race vary in construction and are unique to the course. We classified fences into seven different categories: plain fences (no ditch), open ditch (ditch in front), first fence, water jump, Becher's Brook (ditch on landing side), Canal Turn (sharp turn immediately after a plain fence) and The Chair (high fence with a big ditch in front).

Our results indicate that increasing the schooling of horses over fences of the type used for the Grand National, or in qualifying races over the Grand National course, and providing good-to-soft ground would improve completion figures and decrease the risk of horses falling during the race. The greater risk of falling at the first fence indicates that interventions involving this obstacle could have a big impact on the number of horses that complete the race.

These findings also illustrate the value of using epidemiological methods to identify risk factors for injury in competitive sport and should inform the efforts of the racing

industry to safeguard equine welfare in the Grand National steeplechase.

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Microperiodic structures

Direct writing of three-dimensional webs

Applications are emerging that require the creation of fine-scale structures in three dimensions — examples include scaffolds for tissue engineering[1], microfluidic devices[2] and photonic materials that control light propagation over a range of frequencies[3]. But writing methods such as dip-pen nanolithography[4] and ink-jet printing[5] are either confined to two dimensions or beset by wetting and spreading problems. Here we use concentrated polyelectrolyte inks to write three-dimensional microperiodic structures directly without using masks. Our technique enables us to write arbitrary three-dimensional patterns whose features are nearly two orders of magnitude smaller than those attained with other multilayer printing techniques[6].

For this direct-write process, we have developed fluid inks that flow readily through fine deposition nozzles and solidify rapidly in a coagulation reservoir (Fig. 1). The inks are made up of concentrated polyelectrolyte complexes that consist of non-stoichiometric mixtures[7] of polyanions (polyacrylic acid, PAA) and polycations (polyethylenimine, PEI, or polyallylamine hydrochloride, PAH). By regulating the ratio of anionic (COO^-Na^+) to cationic (NH_x^+) groups and combining these species under solution conditions that promote polyelectrolyte exchange reactions[8], we produce homogeneous fluids (40–50 wt % polyelectrolyte in aqueous solution; for methods, see supplementary information) with the requisite viscosity (about 5–150 pascal seconds) for deposition through microcapillary nozzles of varying diameter (0.5–5.0 μm).

When deposited in an alcohol/water coagulation reservoir, these concentrated polyelectrolyte inks coagulate to form self-supporting filaments or rods (Fig. 1). The reservoir composition strongly affects both the ink's elasticity and the coagulation mechanism, which is driven by electrostatic effects in water-rich reservoirs and by solvent effects in alcohol-rich reservoirs. For example, the elasticity of PAA/PEI ink (ratio of anionic/cationic groups: $[COO^-Na^+]/[NH_x^+] = 5.7$) rises dramatically from 1 Pa (fluid phase) to nearly 10^5 Pa (coagulated phase) upon deposition in a reservoir containing 83–88% isopropyl alcohol. Under these conditions, the deposited ink filament is elastic enough to retain its shape while being able to flow and adhere to the substrate and underlying patterned layers.

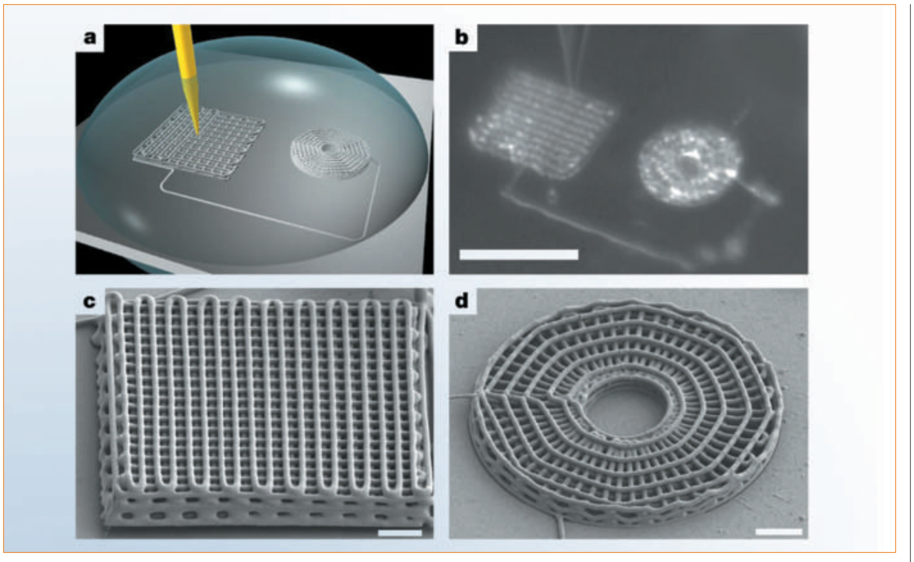

Figure 1 Direct-write assembly of three-dimensional microperiodic structures. **a,** The ink-deposition process (not drawn to scale). A concentrated polyelectrolyte ink is housed in a syringe (yellow) immersed in a coagulation reservoir (grey hemispherical drop) and deposited on to a glass substrate (light grey). **b,** Optical image acquired *in situ* during deposition reveals the features drawn in **a**, including the deposition nozzle that is patterning a three-dimensional lattice, as well as a completed radial array. This image is blurred by the reservoir (scale bar: 100 μm). **c,** Three-dimensional periodic structure with a face-centred tetragonal geometry (filament diameter: 1 μm; 10 layers; scale bar: 10 μm). **d,** Three-dimensional radial array (filament diameter: 1 μm; 5 layers; scale bar: 10 μm).

Images of three-dimensional microperiodic lattices and radial arrays assembled from the PAA/PEI ink are shown in Fig. 1c, d. These structures can have solid or porous walls and rod-like filaments that span the web, as well as tight and broad-angled features. A three-axis (x,y,z) micropositioning device deposits the ink, sequentially building layered, patterned structures (see supplementary information). After producing a two-dimensional patterned layer, the nozzle is raised in the z-direction to generate the next layer. The process is repeated until the full three-dimensional structure is fabricated (building time is about 5 min).

The versatility of these inks is demonstrated by microperiodic structures made from PAA/PAH ink ($[COO^-Na^+]/[NH_3^+] = 0.5$), which consist of a patterned array of polyelectrolyte filaments with a net positive surface charge (see supplementary information). These three-dimensional polyelectrolyte scaffolds open up new opportunities for the electrostatic layer-by-layer assembly[9] of materials, which has previously been limited to thin-film[9] or discrete colloidal structures[10].

Direct-write assembly is a powerful way to create three-dimensional microscale structures of arbitrary design and functionality. A variety of inks could be developed using other polyelectrolyte mixtures, based for example on biologically, electrically or optically active polyelectrolytes. The structures created could direct cell-scaffold interactions[11], manipulate fluid flow[2], control light propagation[3], or respond to environmental stimuli[12].

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