Cytoskeletal structures in epithelium and the Millennium Bridge balance the forces of tension and compression

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Rule to Build By:

It can be seen in both man-made and nature-made structures that the balance of tension and compression forces is necessary in order to construct self-supporting structures (Morris, Lane, 2012).

What:

Epithelial cells and the Millennium Bridge in London, England are good examples of this architectural principle.

How:

The cytoskeleton of epithelial cells serves as a method to balance the forces of tension and compression. Microtubules are hollow tubes that originate from the centrosome and are made of tubulin dimers arranged in protofilaments (Alberts et al., 2010). Microtubules are the most rigid of the cytoskeletal filaments (Fletcher and Mullins, 2010), and thus microtubules have the ability to bear relatively large compressive forces. This ability is augmented by the surrounding cytoskeletal network as shown in Figure 1. Without the cytoskeletal framework, the microtubules would experience greater displacement (Brangwynne et al., 2006). It is also important to note the microtubule's dynamic nature, as they polymerize and depolymerize in response to the presence or lack of capping proteins (Alberts et al., 2010).

Intermediate filaments show great tensile strength and serve an important role in epithelial cells. They span each cell connecting to the cell membrane at desmosomes. When under stress, the intermediate filaments distribute the force over the filaments as opposed to just the cell-to-cell junctions. This is illustrated in Figure 2. The staggered tetramer made of two dimerized coiled-coils gives the intermediate filament ropelike strength (Alberts et al., 2010). In epithelia, the most prominent group of intermediate filaments the keratin family (Alberts et al., 2010).

Actin contributes to the cytoskeletal network's balance of forces as well. Actin is made up of globular actin protein subunits arranged in a twisting chain-like formation (Alberts et al., 2010). The many binding mechanisms of actin allow it to be constructed into several conformations, and each binding pattern has its mechanical advantages (see Figure 3 for examples). Actin filaments in the cell cortex are bound by cross-linking proteins, which arrange the filaments into a meshwork (Alberts et al., 2010). This arrangement resists tension (Gerdelmann and Pawlizak, 2009). When actin filaments are bound by bundling proteins, the filaments take a parallel alignment. This works to resist compression (Morris, 2012). A branched conformation accomplishes this as well (Fletcher and Mullins, 2010).

The dynamic interactions between these three groups of cytoskeletal filaments allow the cells to function as necessary in their respective locations but the balance of tension and compression is necessary for success. For example, if microtubules and intermediate filaments are removed and the cell undergoes mechanical stress, the actin conformations will change as the result of breaking and reforming the structures, leading to deformities in the cell's shape (Wang, 1998).

An important observation that distinguishes the cell structure and the Millennium Bridge deals with the notion of tensegrity. As defined by the Oxford Dictionary, tensegrity is the "characteristic property of a stable three-dimensional structure consisting of members under tension that are contiguous and members under compression that are not" (Oxford Dictionary, 2010). This allows cells to be dynamic and react to stimuli. Cells are not completely rigid and there is leeway that allows for cell movement or adjustment (Ingber and Jamieson, 1985; Morris, 2012). While epithelial cells are attached to a basement membrane and are therefore immobile, they still must react to pressure and pulling, as epithelial cells are the most exposed cells of the body, whether as part of the integument or the lining of the gastrointestinal tract. When you swallow food, your esophagus gives way to the food, this is because the cells have the ability to maintain a stable state due to tensegrity (Ingber and Jamieson, 1985).

The Millennium Bridge in London exemplifies this principle in its construction. As you can see in Figure 4, the cables that run horizontally distribute tension forces over the length of the bridge and are functionally similar to actin and intermediate filaments especially. Figure 4 illustrates the point of tension braced by connectors that connect the cables. These connectors can be compared to the desmosomes embedded in the plasma membrane. Also illustrated in Figure 4 are the mechanisms of compression bearing. These function similarly to microtubules.

Why:

Without a balance of compression and tension, instability and collapse are the likely result. One of the main jobs of the cytoskeleton is cellular organization (Alberts et al., 2010). Large changes in cytoskeletal structure can be detrimental to the cell's function. For example, microtubules are largely responsible for the general layout of the cell and the distribution of organelles (Alberts et al., 2010). Intermediate filaments also help to maintain cellular organization under stress, as does actin (Wang, 1998). If one of these filament types were missing or not functional, the cell would undergo significant changes in layout and would be structurally unstable. The necessity for cytoskeletal filament interaction can be supported by the fact that it is shown to be advantageous for cells to evolve with proteins that link the different cytoskeletal filaments such as plectins (Fletcher and Mullins, 2010). An excellent example of this is how the tension of actin and intermediate filaments is necessary for the prevention of large scale buckling of microtubules (Brangwynne et al., 2006). In addition, the lack of intermediate filaments in epithelial cells would result in their rupture when pulled (refer to Figure 2). The nuclear lamin subset of intermediate shows importance through the diseases (such as the varieties of progeria) that present themselves when nuclear lamins are defective. The believed cause is a structural instability in the nucleus that prevents the cell from functioning properly (Alberts et al., 2010).

The Millennium Bridge is a high-tension bridge that is built using lateral suspension. The great amount of tension put on the cables must balance with the compression of the concrete "V" brackets (Dallard et al., 2001). The necessity for the balance of tension and compression in the Millennium Bridge is exemplified by its opening day. When pedestrians began to cross the bridge, it wobbled, frightening many of the thousands who traversed the bridge that day (BBC News 2000). In response, the bridge was closed, deemed unsafe. To mend this the bridge was fitted with shock absorbers, which function on the principle of compression and extension (Harris, 2012).

Figures:

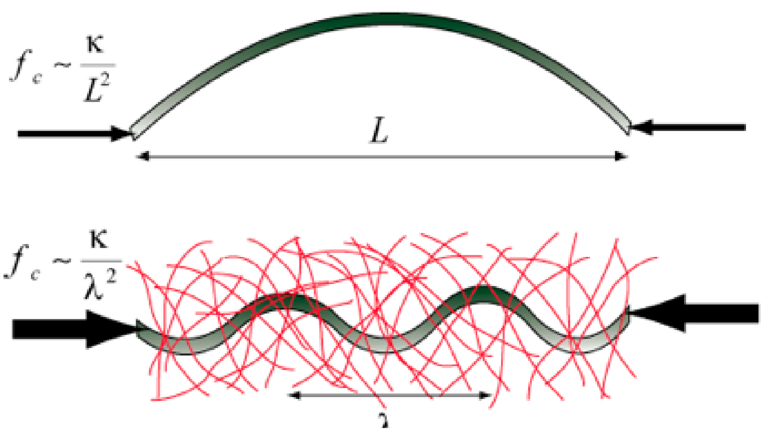

Figure 1: Elastic cytoskeleton supports microtubules. This image illustrates the difference in microtubule buckling when the surrounding cytoskeletal filaments are present and when they are not. Notice the difference in the amunt of force put on the two microtubules (represented by the thickness of the black arrows). The top microtubule experiences a weaker compression force and experiences a large-scale displacement, while the bottom microtubule is under a greater amount of force and experiences less displacement (Brangwynne et al., 2006).

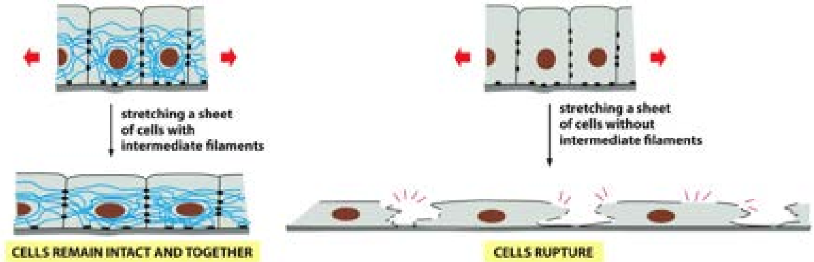

Figure 2: Distribution of tension forces by intermediate filaments in epithelia. This image demonstrates the importance of the intermediate filament network in epithelial cells. The filaments distribute tensile forces across the cell. This prevents the tearing of the plasma membrane at cell-to-cell junctions (Alberts et al., 2010).

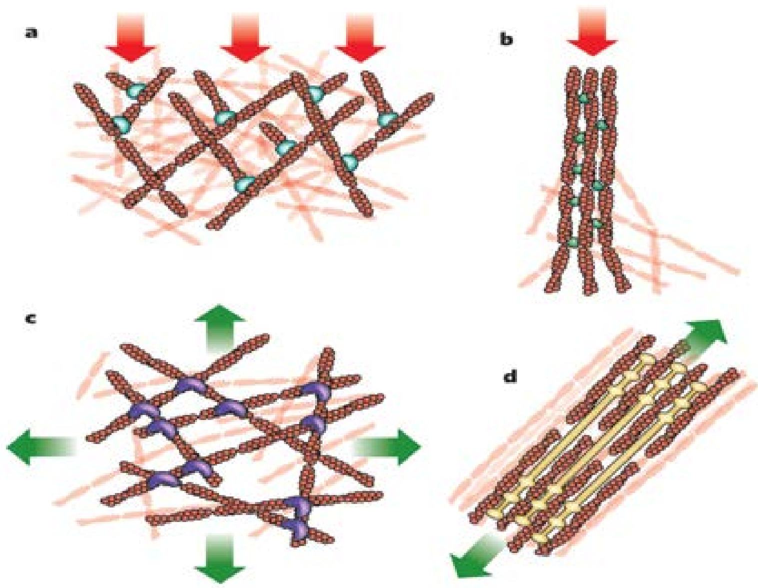

Figure 3: Various structural layouts of actin and their forces they withstand. Actin arrangements a. and b. withstand compression forces. while formations c. and d. undergo tension forces. It is important to note that arrangement b. is not present in epithelial cells, but in the filopodia of mobile cells (Fletcher and Mullins, 2010. http://www.nature.com/nature/journal/v463/n7280/fig_tab/nature08908_F3.html/) .

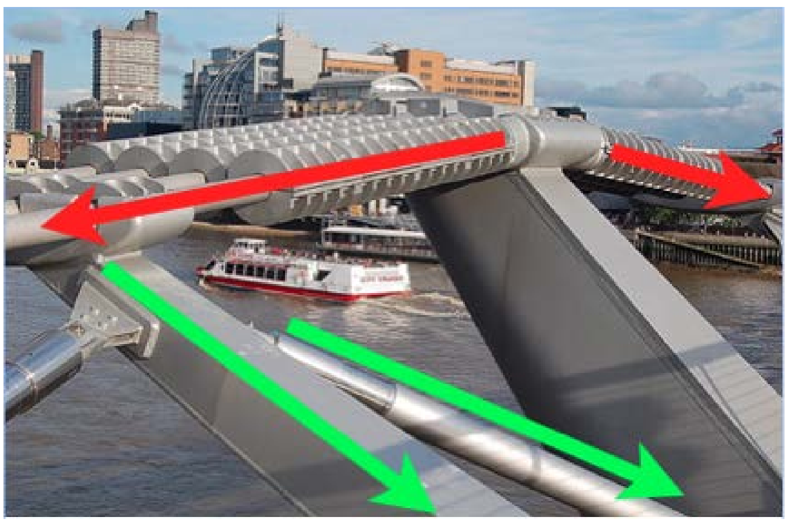

Figure 4: Tension and compression in the Millennium Bridge. In this image the connectors serve a similar function to the desmosomes as they connect the cables at junction distributing the tension forces (shown with red arrows) horizontally over the length of the bridge. The upward supports and hydraulic cylinders bear the compression forces (shown with green arrows) much like the microtubules bear compression forces in cells. (http://zoesknittingbag.typepad.co.uk/my_weblog/images/2007/06/17/close_up_millenium_bridge_160607.jpg edited by Lindsey Gillis).

Figure 5: Full view of the Millennium Bridge in London, England.
http://www.aviewoncities.com/gallery/showpicture.htm?key=kveen1256

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